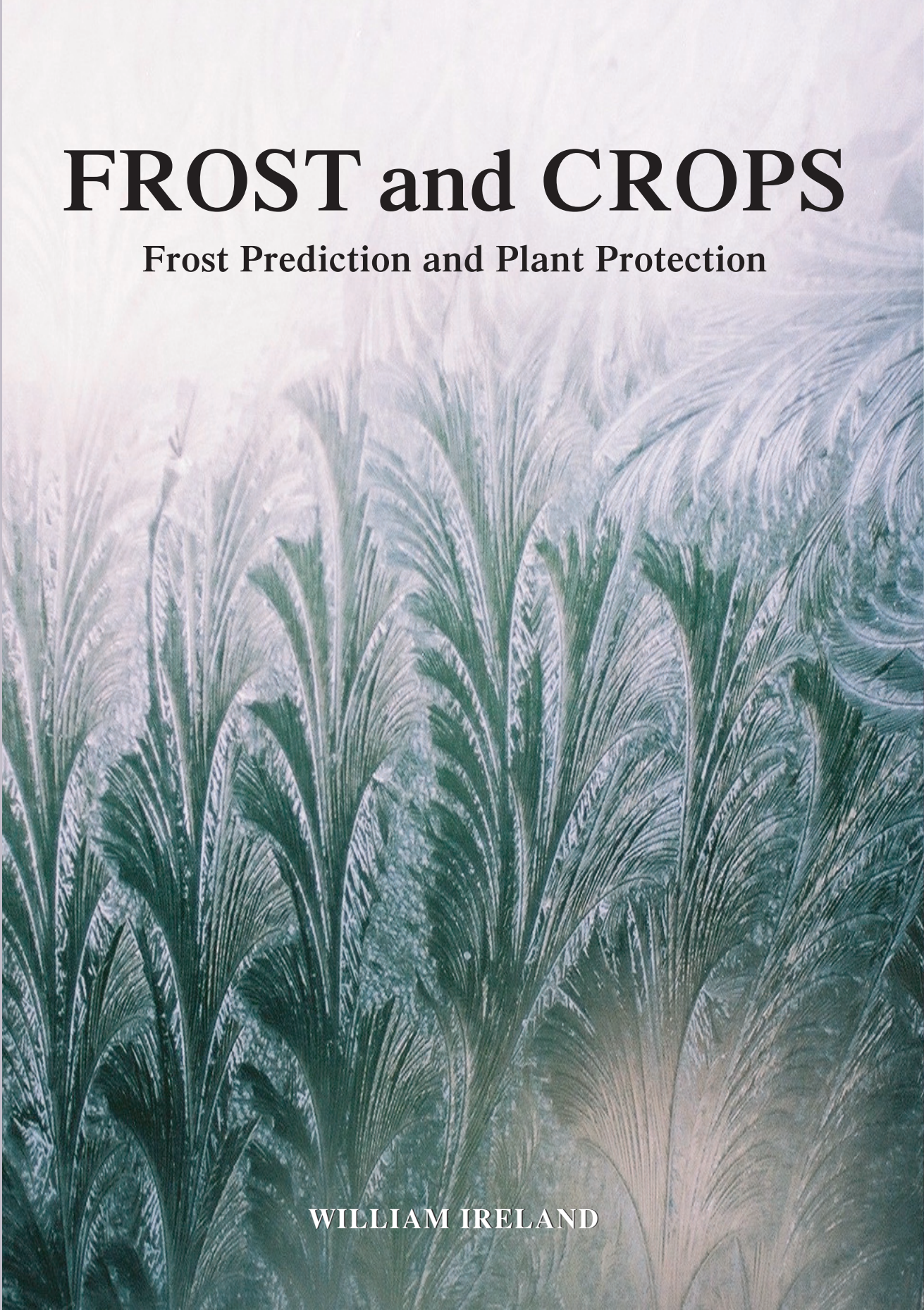
FROST and CROPS

Frost Prediction and Plant Protection



WILLIAM IRELAND

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“If I have seen further it is by standing
on the shoulders of giants”

Sir Isaac Newton

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PREFACE

When I was employed with the Physics and Engineering Laboratory of the New Zealand Department of Scientific and Industrial Research I experimented in laboratory and field with methods for frost fighting in commercial orchards. I often came up with the problem that I could not find the answers to my questions in a readily available book. An up-to-date textbook, bringing together the published results of representative practical frost protection methods, was required. I came to the conclusion that I should find the answers and write the book myself. I also considered that it was vital for the book to explain how frost occurs, its relation to climate and geography, and how plants are damaged or adapt to frost.

This book is the result of my research. It is a reference book on frost prediction and the protection of crops from frost damage. It is based on refereed texts from the scientific literature, books, and my own experience with frost and frost protection over the last twenty-five years. It has been written to bridge the gap between the scientific literature and the needs of horticulturalists, their technical advisers and engineers. An underlying hope was that I would find the description of a simple practical method for on-site overnight temperature prediction. This happened recently when I realized that the cooling in a radiation frost is a classic example of Isaac Newton's 'law of cooling' and that the temperature at any time after sunset may be predicted using temperature measured with a single thermometer.

The first seven chapters give a general description of frost, frost prediction and protection, including how to use Newton's law. The last six chapters deal with the published results of specific frost prediction and protection experiments and the results they have achieved. The emphasis is on the description and evaluation of the various experiments, and no attempt is made to compare their capital and running costs, nor to research material on yield loss due to frost damage.

A key feature of the book is that it quantifies the frost protection achieved by the methods that are commonly used. Following general practice, a model is used that assumes that the heat lost by infrared radiation from the earth surface at night is approximately balanced by the heat convected to the surface from the air and conducted from below ground. A similar assumption is used to model the heat flow from and to a crop. The text has been kept as simple as possible, but is fully referenced for those wishing to refer to the original texts for further information.

CHAPTER ONE

DEFINITIONS

INTRODUCTION

Climate controls the distribution of plant species in several ways. There must be sufficient heat in the growing season and enough cold days in winter, but freezing of plant tissues is the single most important factor limiting natural plant distribution. The productivity of cultivated plants is also strongly dependent on freezing injury, generally the result of overnight frosts. In many places plants can be grown successfully only if some form of frost protection is carried out.

This monograph describes frost and its effect on plants. It discusses methods used to protect crops from frost damage. The source material has been carefully selected from the popular and specialist peer-reviewed frost literature. It includes previously unpublished research findings of the author and his colleagues during several years of practical frost research, including many very cold nights spent frost fighting in orchards.

FROST FORMS

Frost takes many forms and has been personified and dreaded through the ages. Frost lore records the sayings, 'Clear Moon frost soon', and 'Frost on the shortest day indicates a severe winter'. The first saying ignores the fact that frosts also occur on clear moonless nights; the second has no rational basis.

'Father Frost' is a white old man in Russia and 'Old Mother Frost' appears in German folk tales.

'Jack Frost' is a legendary elf-like being who possibly originated in Norse mythology. Jokul (Icicle) and Frosti (Frost) were the names given to the son of Kari, the God of the Winds. Jack Frost is supposed to be responsible for drawing the patterns sometimes found on frosted surfaces:

> 'These winter nights, against my window pane
> Nature with busy pencil draws designs
> Oak-leaf and acorn and fantastic vines,
> Of ferns and blossoms and fine spray of pines,
> Which she will make when summer comes again-
> Quaint arabesques in argent, flat and cold,
> Like curious Chinese etchings.'
>
> -T. B. Aldrich.

'Dew' results from the condensation of water on to surfaces above 0°C as the air cools overnight. Tefnut, goddess of moisture, was the personification of dew in Egyptian mythology. Her tears fell to the ground as she helped her twin (husband) Shu, god of the air, atmosphere and dryness, support Nut, the sky. Each morning she received the newborn Sun, Kephri the scarab beetle, as it rose over the eastern horizon.

Frost results when the temperature of the air or exposed surfaces goes below the freezing point of water and either water vapour or dew freezes. Ice in various forms may be present, plants and animals may be damaged by 'frostbite' or killed by exposure, and rocks may be shattered.

The common 'radiation frost', when ice forms on surfaces exposed to the sky, is caused by the overnight loss of heat from the earth's surface by long wave infrared radiation. It generally lasts up to a few hours and is thawed by sunshine next morning. It causes crop damage that can often be prevented by some form of frost fighting technique or equipment.

The rare 'advection frost' or 'freeze' results from large-scale movement of a sub-zero or polar air mass. It may last several days, bringing widespread devastation of crops. Unseasonable snowfalls can also produce frost conditions and cause extensive crop damage.

'Air frost', also called 'screen frost', occurs when the air temperature 1.3m above ground falls below 0°C. Air frost usually damages exposed frost-tender parts of plants.

'Black (or brown) frost' may occur when the air is very dry. Air and surface temperature will be below zero but ice is not present. It usually occurs in autumn, the only indication of its presence being the blackening of tender vegetation.

'Columnar frost' is a mass of hair-like crystals that grows upwards from the ground because water expands when it is drawn upwards and freezes near the surface.

'Fern frost' is often known as 'Jack Frost's Garden'. It takes the form of fern-like patterns on glass surfaces such as the car windscreen shown on the front cover or on house windows. Fern frost is but one of the many crystalline ice forms known as 'hoar frost' or 'true frost'. 'Frost flowers' grow in the same way as columnar frost.

'Frost heaving' occurs when water-saturated soil freezes and ice crystals grow upwards, forcing the soil or vegetation ahead, 'heaving' it out of the ground. Frost heave destroys roads, cracks masonry, and displaces building foundations. When the water in cracks in rocks freezes the rocks may be shattered. The large recumbent stone of the ancient monument 'Loanhead of Daviot' in Scotland has been split in two by frost. Erosion due to frost is also responsible for some spectacular landforms such as the 'hoodoos' and pinnacles of Bryce Canyon in USA.

'Glazed frost', also known as 'freezing mist', 'freezing rain', 'glaze', or 'ice storm', appears when a layer of clear smooth amorphous (non-crystalline) ice forms on cold surfaces when super cooled rain or drizzle freezes. Glazed frost may also be called 'black (or brown) ice'. It may be found on roads, where it is transparent and invisible, creating extremely dangerous conditions, and bringing traffic to a standstill. It may build up on tree branches or telephone and power lines until they break under the strain.

'Ground frost' is said to occur when the 'grass minimum temperature' is -1°C or below. Ground frost not accompanied by air frost does not usually damage plants when the time spent below zero is short.

'Hoar frost', so called because it gives plants a hoary aged look, forms when water vapour crystallises as ice without first condensing as liquid water (dew). The process is sometimes called 'sublimation' but is more correctly 'deposition', sublimation being the change from solid to vapour without going through the liquid (dew) stage. Exposed surfaces with a feathery covering of ice crystals indicate a 'crystalline frost', produced when the water vapour freezes on surfaces that are below 0°C. In 'white frost' the crystals are coloured white. Hoar frost has several crystalline forms that take their names from the crystal shapes. 'Needles' is an assemblage of parallel hexagonal columns 0.2 to 0.5mm diameter and up to 10mm long. 'Feathers' up to 50mm long found in 'depth hoar' are composed of small hexagonal columns, some attached at right angles to others. Hexagonal 'plates' sometimes grow from wooden surfaces. 'Cups' occur in depth hoar; when fully developed they resemble hexagonal whisky glasses. 'Dendritic' crystals of branching or 'tree-like' forms are sometimes found (coincidentally) on tree branches on calm frosty mornings.

'Icicles' are tapered hanging spikes of ice formed when water dripping down from a surface such as the roof of a cave freezes. They may be accompanied by 'hydromites' growing upwards from the ground below.

'Killing frost' occurs when air temperature falls below about -2˚C; there is widespread plant damage and many plants are killed.

'Rime' is the ice produced when cloud or fog droplets freeze on contact with solid surfaces such as tree branches or power lines; it is white or opaque when air is entrained within the ice. Rime 'feathers' form on exposed objects when there is a wind; the ice grows into the wind.

TEMPERATURE

Confusion may arise if the word 'temperature' is used alone. It should always be qualified by a word such as 'air', 'critical', 'average', or 'mean', to indicate clearly the object whose temperature is being measured, and whether it is a single measurement, or an average of several (average), or half way between two extremes (mean). Even 'air temperature' may be of dubious value, as it depends on the height above the surface at which the measurement was made, and the construction of the thermometer used to measure it.

In this monograph references to temperature will be clearly stated in standard meteorological terms. All temperatures will be given in degrees Celsius (˚C), except in formulas for calculating infrared radiation, when they are given in degrees absolute (Kelvin). The temperature intervals one degree Celsius and one degree Kelvin are identical, but 'Absolute Zero', written '0K', is 273.15 degrees below the melting point of ice, 0˚C. Thus

$$0^{\circ}C = 273.15K$$
$$\text{and } 0K = -273.15^{\circ}C.$$

'Average temperature' is not synonymous with 'mean temperature'; it is the arithmetic mean of several measurements of the actual temperature made at uniform time intervals during the relevant period. (If only two measurements are made then mean and average are numerically equal.)

'Critical temperature', the temperature at which plant tissue is damaged by ice is rarely stated in the frost protection literature. Critical temperature depends on the season and the stage of development of a plant. In winter the critical temperature of hardened tissue may be below -20˚C, in spring the critical temperature of buds and new growth may be only one degree below zero.

'Dry bulb temperature' is the temperature indicated by a liquid-in-glass thermometer (often mercury) in air when the outer surface of the bulb is kept dry.

'Grass minimum temperature' is recorded by an exposed minimum spirit thermometer supported horizontally with its bulb 25mm above a clipped grass surface.

'Ground (or surface) temperature' may be confusing. In a radiation frost the effective surface is the surface that radiates infrared heat energy towards the sky. When the ground is bare, or covered by an opaque material such as bitumen, the effective surface is the upper surface of the soil or the covering material. The effective surface may be poorly defined if the ground is covered by vegetation. It will then be at some intermediate level between the soil and the top of the vegetation. Accurate measurement of 'surface' temperature is difficult and rarely attempted. Temperature below ground is however, reliably measured, and the 'ground surface' temperature can be computed from the belowground value.

'Mean temperature' is often quoted in meteorological texts because temperature is recorded with 'maximum' and 'minimum' thermometers. Then the mean temperature is the arithmetic mean of all the maximum and minimum temperatures recorded during the relevant period, such as a day or a month.

'Radiation temperature' of a surface is the temperature of a black surface that radiates energy that is equivalent to that radiated by the surface.

'Screen temperature' is a standard meteorological term for the temperature indicated by a dry bulb thermometer, enclosed in a louvered 'Stevenson' screen 1.3 metres above a grassed surface. This is assumed to be the temperature of the air 1.3m above ground, the enclosure having 'screened' the thermometer from radiant heat sources such as the Sun, which would cause the thermometer to give an erroneous reading.

'Sky temperature' is the temperature of a hypothetical black surface overhead that has the radiation temperature of the atmosphere.

'Wet bulb temperature' can be used in conjunction with 'dry bulb temperature' to calculate atmospheric humidity. It is the temperature of a liquid-in-glass thermometer (often mercury) whose bulb is enclosed in a cotton wick that is kept wet by being connected to a water reservoir. The wet bulb is exposed to the air, and the wet bulb temperature lies below the ambient air temperature because the evaporation of water from the wick has a cooling effect. A combination of wet and dry bulb thermometers is known as a 'psychrometer'. The highest accuracy is achieved when the thermometers are aspirated so that the air passing the bulbs has a velocity of at least 3 metres per second

HUMIDITY, DEW POINT AND FROST POINT

The amount of water vapour present in a parcel of air is known as the 'Absolute Humidity' when measured either as mass per unit volume at a given temperature, or as a partial pressure. 'Specific Humidity' is the mass of water vapour per unit mass of air (including the mass of the water vapour). 'Mixing Ratio' is the ratio of the mass of water vapour to the mass of dry air. The amount of water vapour that can be present in the atmosphere decreases as the air temperature is lowered. At the temperature where the atmosphere is saturated with water vapour the 'Relative Humidity' is said to be 100% and the air temperature is known as the 'dew point' or on occasion the 'frost point'. All three temperatures, wet bulb, dry bulb, and dew point are equal when the relative humidity is 100%. Above the dew point air is 'unsaturated' and relative humidity is less than 100%, so dew tends to evaporate; below the dew point dew may sometimes not be nucleated and relative humidity will be more than 100%; the air is said to be 'supersaturated'. The dew point can be either above or below 0°C, depending on the amount of water vapour in the air. When the air temperature falls below the dew point mist and fog droplets may form on any of the microscopic 'nucleating particles' present in the air. Dew forms when atmospheric water vapour condenses to tiny drops of water on exposed surfaces that are colder than the dew point.

The 'frost point' is the temperature at or below 0°C at which the humidity of air is 100% relative to ice. The frost point is slightly warmer than the dew point. Frost forms on the exposed surfaces of objects in either of two ways: when dew freezes, or else when atmospheric water vapour turns directly to ice. The ice continues to grow so long as the surfaces are colder than the frost point. Very heavy coatings of ice can build up and may eventually cause the objects to break under the strain. Dew may freeze on objects to amorphous ice, rather than the crystalline forms referred to as true frost formed when water vapour turns directly to ice (deposition). Hoar frost crystals can be formed when the water vapour is

deposited on suitable nucleating particles or surface features. Alternatively, if the surface has already cooled to the dew point, and dew has formed, ice can be nucleated by particles within the dew, initiating the freezing of the dewdrops because they are already colder than the frost point by a fraction of a degree (at about -2˚C the dew point is 0.25˚C colder than the frost point). The vapour pressure over dew is higher than over ice at any given temperature below 0˚C, so air that is saturated with respect to ice is unsaturated with respect to dew. Once some of the dewdrops have frozen others may be seen to evaporate and the ice crystals nearby grow quickly. The water is transferred from the evaporating dewdrops to the ice crystals through the vapour phase (Hardy et al 1982). Another effect of this difference between dew point and frost point below 0˚C is that a wet bulb thermometer can be warmer than a dry bulb when the water condensing on the wet bulb releases latent heat. The relationship between frost point and dew point from -12 to 0˚C is shown in Figure 1.1 (Washburn 1928).

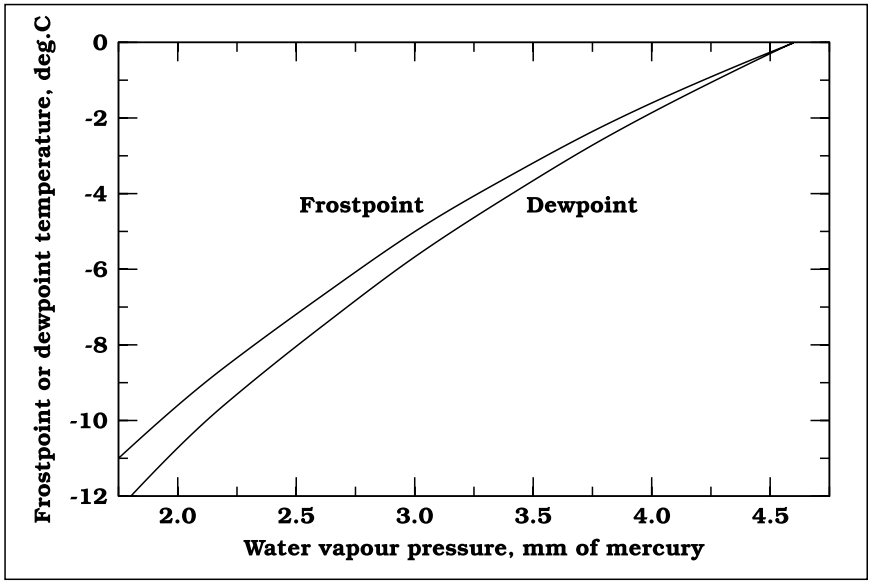

FIGURE 1.1. The relationship between water vapour pressure and the temperature at which the atmosphere is saturated with respect to ice (the frost point) and with respect to water (the dew point). (Data from Washburn).

BUOYANCY

When the pressure on a 'parcel' of air is reduced the air expands and cools. Pressure reduces with height and as a result the temperature of air generally falls as it is taken upwards. Warm air is less dense, and thus more buoyant, than cool air at the same pressure or height above ground. 'Adiabatic equilibrium' occurs when a parcel of air can be taken from one height to another and when released it stays there, because its buoyancy matches that of the surrounding air. The atmosphere is in 'dry adiabatic equilibrium' if its temperature falls approximately 1˚C per hundred metres of elevation above ground. The normal sunny day situation near the ground is when 'lapse' conditions exist, the air temperature falls more

than 1˚C/100m, and vertical convective mixing may readily occur as warmer air near the surface rises through cooler air above. On clear frosty nights with low wind speed the air temperature will fall less than 1˚C/100m, and a 'temperature inversion' is said to exist when the air close to the surface is cooler than that higher up; vertical mixing is suppressed because the less dense, more buoyant, warmer air is already above the cooler air near the surface.

'Katabatic flow' is a down-slope wind of the cold air nearest the surface of sloping ground on a frosty night, caused by the cold air sliding under, rather than mixing with, the warmer air in the temperature inversion above. In deep and narrow river valleys cold air will flow down the hillsides overnight, ponding on the valley floors, giving colder than expected frosts and poorly developed temperature inversions. The air near the surface can be even colder than the surface over which it is drifting. The katabatic flow or downhill drift of cold air is a localised form of advection frost, rather than a purely radiation frost.

WATER

Water exists freely in the three forms: solid (ice, hail, snow), liquid (water, rain, fog, cloud, steam), and gas (water vapour), or with other compounds in solutions and crystals.

The density of pure liquid water at atmospheric pressure depends on temperature; at 0˚C it is 999.87kg/m^3, at 3.98˚C it has maximum density, 1000.00kg/m^3, and at 10˚C it is 999.73kg/m^3, with the curious result that ice forms first on the surface of ponds in a frost and thickens downwards. The density of ice is about 916kg/m^3, and icebergs float with only about 8.4% of their volume above the water surface.

'Sensible' heat, so called because the temperature change that it causes can be detected by the senses, is the heat that flows into or out of a substance as it is heated or cooled, without causing any change of state. The average sensible heat of ice between melting point and -20˚C is about 2.05J/g/˚C, of water between 0˚C and boiling about 4.186J/g/˚C, and of water vapour at 100˚C and constant volume, 1.463J/g/˚C. Liquid water has a higher sensible heat than any other known substance. For comparison, the sensible heat of air at constant pressure is about 1J/g/˚C, that of granite and sand about 0.8J/g/˚C, and of iron about 0.5J/g/˚C. 'Specific' heat is the ratio of sensible heat of a substance to the sensible heat of the same mass of water over the same temperature range. The specific heat of water is 1.0.

'Latent' heat is the heat absorbed or released when a substance has a change of state. The latent heat absorbed by boiling water at 100˚C is 2256J/g, the latent heat released when dew condenses from the water vapour in the air at 0˚C is 2500J/g, and a further 334J/g latent heat is released when dew turns to ice.

Reduced pressure decreases the boiling point of water but increases the melting point of ice. At a height of 1000m above sea level the atmospheric pressure is only 89% of that at sea level; water boils at 96.6˚C and ice melts at 0.001˚C, compared with 100.0˚C and 0.000˚C at sea level. The boiling point of water on high mountains can be so low that tea cannot be satisfactorily infused. Small as it is the effect of pressure on the melting point of ice is significant; it is what makes ice so slippery and what allows people to make snowballs. The pressure exerted on an icy surface that is close to 0˚C may lower the melting point enough for some of the ice to melt; it may freeze again when the pressure is removed. A person standing on an ice skate may easily produce enough pressure to melt the ice below the skate so that it slides freely; if the ice is too cold melting does not occur and the ice is not slippery. Similarly, if snow is too cold the pressure produced by squeezing it in the hands is insufficient to melt the snow and the ball will not make. The lowering of the melting point of ice is 0.0075˚C/atmosphere (Roberts 1942).

The latent heat of fusion when dew turns to ice is 80 times as much, and the total latent heat, 2834J/g, released when water vapour is turned to ice in a hoar frost, is about 670 times as much heat as would be given up in cooling the same quantity of liquid water from 1˚C to 0˚C. The latent heat of fusion of water (334J/g) is a very convenient source of the enormous amount of heat needed for frost protection. Freezing 120 litres of water per hour will release as much heat as burning one litre of fuel oil.

FREEZING AND MELTING POINTS

Clean water in a clean container and not in contact with ice will not begin to freeze spontaneously until it is cooled to -38.1˚C. If it contains solutes or electrolytes, or is contained within very small pores, it must be cooled even more before the chance formation of enough appropriate structures in the water is sufficient for 'homogeneous nucleation' to start freezing.

In order for super cooled water to begin to freeze at temperatures close to 0˚C minute particles of ice or other substances or surfaces having particular characteristics must be present. Then 'heterogeneous nucleation' takes place and ice crystals grow on the 'nucleating particles' or surfaces. The particles and surfaces must have structures that match the lattice of hexagonal ice crystals in order for heterogeneous nucleation to occur and ice crystals to grow.

In nature and on plant surfaces in frosts water usually super cools to the order of -1 to -2˚C, and sometimes much more before ice forms. Once ice forms further ice can grow very quickly at temperatures up to the freezing point, but not above the melting point, and not above 0˚C. Water cannot freeze quickly if it is at 0˚C because of the heat released on freezing. There must be some way of conducting or radiating the heat away from the freezing front. Freezing of 0˚C water would be infinitely slow, but the speed of freezing of water colder than 0˚C increases exponentially as the super cooling is increased (Hobbs 1974). As a result, super cooling prior to ice nucleation on a plant surface in a frost is a potentially hazardous phenomenon. The greater the super cooling the greater is the likelihood of damage from 'non-equilibrium freezing'.

It is important to be aware of the distinction between the 'freezing point' of water and the 'melting point' of ice. The freezing point of pure water and the melting point of ice in pure water are the same, 0˚C (273.15K), but the freezing point of impure water is often lower than the melting point of ice. Ice will not melt until it is heated to the melting point. The presence of solutes or other substances lowers both the freezing point and the melting point, and may lower the freezing point more than the melting point, introducing an hysteresis in addition to an 'antifreeze' effect. The freezing point of a solution containing ice lowers as the ice builds up because the water remaining unfrozen decreases while the solute remains constant. The melting point of ice in normal cell sap of most plant species of agricultural importance is usually between -0.5 and -2˚C and rarely as low as -4˚C.

CHAPTER TWO

CLIMATE CHANGE

INTRODUCTION

Ambient temperature at the Earth's surface stays above 10˚C only in the tropical lowlands of the Amazon, the Congo and parts of Southeast Asia. Frosts and below-freezing temperature are experienced over two thirds of the world land mass while the temperature falls below -10˚C over half. In the North of Siberia, Canada and Alaska the winter temperature can regularly fall below -90˚C. Long-term changes in ambient temperature have occurred in the past and are expected to happen in the future, with consequent changes in climate and in the occurrence and severity of frost. Short-term reductions in ambient temperature and the resultant increase in frost occurrence have resulted from volcanic eruptions and from changes in both the El Nino phenomenon and the North Atlantic Oscillation.

THE GREENHOUSE EFFECT AND GLOBAL WARMING

The Earth and atmosphere receive short wavelength radiant heat and light from the Sun and on average lose it all by long wavelength infrared radiation to space. The Sun is a variable star and its heat output has been nearly constant over the last million years or so but it is subject to small short-term cyclic variations such as the '11 year' sunspot cycle. At the maximum of the sunspot cycle the energy reaching the Earth is about 0.05 to 0.15% greater than at the minimum. Over the Twentieth Century the average energy reaching the Earth is believed to have increased by about 0.1% (Parker 1999) and the Sun's coronal magnetic field has doubled (Lockwood et al 1999) while the average Earth surface temperature has increased perhaps 1˚C.

Without an atmosphere the Earth's surface temperature would be about -18˚C. Water vapour and several other trace gases in the atmosphere, including carbon dioxide and methane, act like the glass in a greenhouse (the Greenhouse Effect); they readily allow the short wavelength sunlight in but restrict the escape of the long wavelength heat from the Earth. As a result of the Greenhouse Effect the Earth's surface is about 33˚C warmer than the effective radiation temperature at the top of the atmosphere. The average surface temperature is about 15˚C and the effective radiation temperature at the top of the atmosphere is about -18˚C.

Water vapour is responsible for the major contribution to the Greenhouse Effect (about 30˚C), but opinions differ over the relative dependence of global warming on changes in water vapour and cloudiness and the manmade increase in carbon dioxide and the other trace gases. One school of thought is that the present climate is unnaturally warm (as a result of human activity) and may trigger the early start of the next ice age. The time then required to cool to the point where mid latitudes will support only tundra is believed by some to be possibly as short as thirty years. A preferred notion is that the climate will stay unnaturally warm for several centuries before the next glaciation begins.

The day-to-day changes in atmospheric water vapour and cloudiness are the major contributors to frost variability, the other trace gases having little effect.

GAIA HYPOTHESIS

The Gaia hypothesis put forward the idea that the climate and composition of the Earth's surface, oceans and atmosphere result directly from life on Earth and are maintained at an equilibrium that is optimum for the continued existence of life (a 'homeostasis'). Present day temperatures are believed to be 30 to 50˚C cooler than they would have been if life had not existed on Earth (Lovelock & Watson 1982).

Before life began at least 3,600 million years ago the atmosphere was largely carbon dioxide and oxygen was absent. The large Greenhouse Effect of the substantial amount of carbon dioxide gave high surface temperatures, possibly as high as 100˚C.

Weathering of the rocks by organic acids has removed most of the carbon dioxide from the atmosphere and locked it up as carbonates in the soil or in solution in the oceans. Strong evidence suggests that the amount of carbon dioxide in the soil and the rate of weathering of the rocks have been significantly enhanced by the soil bacteria. The present atmospheric constitution and surface temperature are believed to be a direct result of the present rate of weathering. A global warming may cause the soil bacteria to become more active; this would deplete the soil carbon, increase the atmospheric carbon dioxide, increase the Greenhouse Effect and result in further warming (Schwartzman & Volk 1989, 1991). On the other hand an increasing temperature may make plants grow more profusely, which would remove carbon dioxide from the atmosphere and lock it up in organic compounds.

According to the Gaia hypothesis anaerobic bacteria in rice paddies and wetlands produce methane, playing an important part in holding atmospheric oxygen to about 21%. In the absence of methane, oxygen could rise to the order of 25%, a dangerous level where virtually all vegetation, wet or dry, would burn when ignited. Methane also exists in large quantities in ocean sediments and in clathrates in permafrost. Global warming could release some of this methane, further increasing the Greenhouse Effect warming (Schneider 1989).

LONG TERM TEMPERATURE CHANGES

The Scot, James Croll first published the astronomical theory of the long-term changes in the Earth's surface temperature, known as the Pleistocene glaciations, in 1864. The theory was refined by the Yugoslav, Milutin Milankovic in the nineteen thirties and is now known as the 'Milankovic Model'. It was finally accepted in the nineteen seventies, when isotopes in deep-sea sediments revealed the historical changes in temperature and ice cover of the Earth. The theory is that changes in the Earth's orbit vary the distribution and intensity of incoming solar radiation in a cyclic manner and the climate tends to change as a result.

Instrumental measurements of the temperature at the Earth's surface have been made only since about 1660; average temperatures before this can be inferred from biological and geological data back to about sixty million years ago. It appears that never in the last 3,500 million years have the oceans frozen, nor has the average surface temperature been raised above 50˚C. Yet in the same time the Sun's energy output has increased by some 30% and drastic temperature increases could have been expected.

In the Mesozoic era 100 million years ago the dinosaurs lived in a world believed to have been perhaps 10 to 15˚C warmer than today. Following the extinction of the dinosaurs, average surface air temperature in the tropics may have remained at 25 to 30˚C, but mid latitude temperature may have dropped from 21˚C to only 10˚C. Average polar temperature may have fallen from 10˚C to below -10˚C.

The earliest ice ages were probably in the Proterozoic Age 700 to 1,000 million years ago. They have been followed by many more including the glaciations of the present Pleistocene era. Slightly less than two million years ago the mid latitude temperature developed cyclic variations at the commencement of the glaciations of the Pleistocene era.

There appear to have been about ten cyclic temperature variations or glaciations in the last million years, each glaciation about 80,000 years long, separated from the next by a warm interglacial spell of 10,000 to 20,000 years. The mid latitudes may have been 1 to 3˚C warmer during the interglacial periods and about five degrees cooler during the glaciations than they are today.

The present interglacial period is considered to have begun between 6,500 and 20,000 years ago depending on location. The warmest period may have occurred some 5,000 years ago. Cooling towards the next glaciation is thought to have already begun and is expected to continue for another 23,000 years (Imbrie & Imbrie 1980). This cooling may have been masked during the Twentieth Century by a global warming of about one degree Celsius.

The warming at the end of the last glaciation about 10,000 to 8,300BC apparently had two stages. The temperature rose about 6˚C and forests flourished in Northern Europe, only to be killed wholesale by reversion to low temperatures in 50 to 80 years about 8,800BC. Low temperatures persisted for another 600 or so years before rising again. A sudden change in the general atmospheric circulation is also thought to have happened about this time (Lamb 1969).

The warmest period in recent times was the 'Post-glacial Optimum', called the 'Hypsithermal Interval' in North America and 'Atlantic' in Europe, about 4,000 to 3,000BC when temperatures were 2 to 3˚C warmer and the snowline about 300m higher than in the Twentieth Century. In Britain dense oak forest grew to an elevation of about 800m above sea level. The sea level at that time rose to its present position.

Fluctuations of average annual temperature at mid latitude since the last glaciation are of the order of plus or minus 1˚C. There have been occasions when temperatures have been consistently high or low for upwards of a few hundred years.

The Viking explorations and settlements of the Middle Ages were made possible by the warm conditions and absence of ice in the North Atlantic from 800 to 1200AD. It appears that Europe may have been at least 1˚C, and Greenland perhaps 4˚C, warmer than they were in the early Twentieth Century. This warm period has also been recorded in Japanese history.

Temperatures fell worldwide from 1300AD, reaching a minimum between 1610 and 1640 during the 'Little Ice Age'. Further cold spells occurred between 1691 and 1720 and from 1821 to 1850. The coldest European winter was 1708-09. In Japan three great famines, Genroku 1695-96, Tenmai 1782-87 and Tempo 1833-39, occurred during the Little Ice Age (Maejima & Tagami 1986). In Europe the average winter temperatures were about 1˚C cooler than late twentieth century values and 2˚C cooler than during the Little Optimum.

The average winter temperature in Europe was about 1˚C cooler in the Little Ice Age than the Twentieth Century and the River Thames in England frequently froze (Ford 1982). Queen Elizabeth I strolled on the frozen river and football was played on the ice. Winter sport on the river was a regular feature in the Seventeenth Century and the first 'Frost Fair' was held in the winter of 1607-08. A tent 'city' was built on the ice, and hawkers, sideshows, food stalls and swings were common. Legend has it that King Charles II watched a demonstration of the new sport of ice-skating on the river in 1662-63. Several sketches of the Frost Fairs on the River Thames exist (Herbert 1966). The last Frost Fair was held in 1813-14 when the ice lasted only a few days and an elephant is recorded as having "crossed the Thames a little below Blackfriars Bridge; the singularity of such an animal on the ice attracted a great concourse" (Hardy et al 1982).

The early twentieth century temperatures in Europe were perhaps 1˚C lower than they were in the Thirteenth Century, the period known as the 'Little Optimum'. Temperatures increased globally by half to one degree in the Twentieth Century and the ten years before 1990 were the warmest recorded (since 1680). Temperatures may now be about the same as those experienced during the Little Optimum around 1300AD.

Average annual temperature in the Arctic has risen about 1˚C since 1960, with the greatest increase, 1˚C per decade, in Alaska and northwest Canada. The warming is greatest in winter and possibly the result of a change in atmospheric circulation in the mid 1970-1980 decade that brought warm air to Alaska. At Fairbanks, spring arrived on average eight days earlier in the nineteen nineties than in the nineteen fifties. In mid-Alaska, mean annual temperature a metre below ground rose more than 1˚C and melting permafrost created problems such as holes in the ground ('thermo casts'), collapsing roads and numerous landslides. Tree rings show that there has been no comparable warming in the last 400 years (Hecht 1997).

VOLCANIC ERUPTIONS

Notable frosts have occurred following explosive volcanic eruptions that released large amounts of fine silicate ash and sulphur aerosols into the stratosphere. The ash clouds reduced the solar energy reaching the Earth's surface, but they would have had little effect on the loss of infrared radiation from the surface, and cooling of perhaps 2 to 4˚C is thought to have been possible. It has been proposed that the evidence for these frosts may be seen in damaged tree rings routinely found in both living and dead Bristlecone Pines from California to Colorado, USA (La Marche & Hirschboeck 1984). Two types of damage have been reported: early wood damage in the inner part of a ring due to frost early in the growing season and late wood damage, a zone of small darkened cells formed near the end of the growing season. Two successive nights with temperature of -5˚C are thought to be sufficient to cause the damage.

The eruption of the volcano Huaynaputina in Peru in February 1600 has been identified as the cause of the coldest summer across the Northern Hemisphere in the last 600 years, when the summer temperature in 1601 is estimated to have been about 0.8˚C cooler than the summer mean for the period 1881 to 1960. "The month of June was very colde, frosts every morning" in England; in Italy freezing weather extended into July (Pyle 1998).

It has been suggested that the 'Year without a summer' experienced in North America and Europe in 1816 ('Eighteen hundred and froze to death'), when snow fell in Europe in June and July, may have resulted from the explosion of Mount Tambora, Indonesia, in April 1815 (Stommel & Stommel 1979). About 100 cubic kilometres of debris was ejected and the height of the mountain reduced by 1,280 metres.

NORTH ATLANTIC OSCILLATION

Winter 1683-84 was the coldest in the English instrumental record and known as the 'Long Frost'. The Thames was completely frozen over for two months and the ice was 260mm thick in places. Belts of ice some miles in width formed on the coast of the English Channel, East Anglia and the Netherlands. Near London large forest trees were split by frost (Ford 1982). The atmospheric pressure regime in the 1683-84 winter has been compared with the winter of 1962-63, when high pressure blocking occurred near Iceland, in contrast to the normal situation, with low pressure over Iceland (Manley 1975). The winters of the nineteen

sixties were consistently the coldest in Britain since the eighteen eighties, while the winters of the late nineteen eighties and early nineteen nineties were particularly mild across Europe. These features are linked to the North Atlantic Oscillation, the ratio of the atmospheric pressure in the Azores to that in Iceland. High pressure in Iceland gives a low ratio, with cold northerly and easterly winds in Europe; a high ratio is associated with warm winters, strong westerly winds and storms (Morton 1998).

EL NINO

Frosts that result from El Nino variations in climate are believed to be responsible for alliances between neighbouring communities in the highlands of New Guinea. The customs of these people include a three-stage plan to cope with the shortfalls in harvest of the staple sweet potato crop as a result of frost damage (Couper-Johnston 2000). In some years the frosts at altitudes above 2,250 metres kill all surface growth, including the sweet potatoes grown on mulched mounds. With the minor annual frosts the people rely on having two garden sites, one in the valleys and the other on the slopes. For the loss of harvest caused by more severe frosts they acquire rights to gardens some distance away. For the total crop loss from once-in-a-lifetime frosts, such as those that occurred in 1941, 1972 and 1997, they move family and possessions to lower altitudes, where they rely on hospitality of kinfolk, or pay with pigs if staying with non-family hosts. They may remain with their hosts for several months, or even a few years, until conditions higher up the hills improve.

CHAPTER THREE

ADAPTATION OF PLANTS TO CLIMATE

INTRODUCTION

The natural distribution of plants on the Earth is largely determined by temperature, particularly winter temperature. Not only is the average temperature important, but also the daily and seasonal variations must lie within limits particular to each species. Plants can survive only over a surprisingly small range of temperature at any time or stage of growth. If it is too cold in winter, chilling or freezing injury will result, if it is too warm many plants suffer from inadequate rest. Frost damage is most likely to occur in spring and autumn at the beginning and end of the growing season. Climate change, cold spells and unseasonable winter weather have caused significant damage to plants and crops.

SURVIVAL DURING WINTER

A species is generally perpetuated by the production and dispersal of sexually derived seeds. Survival of an individual plant until it reaches sexual maturity may depend on its resistance to dehydration by drought, on injury induced by cold weather, or its exposure to frost. Plants have evolved several strategies to survive the cold of winter.

The most direct frost protection strategy employed by a few plant species is known as 'thermoregulation'. The inflorescences of several species of lily and palm and the male cones of some cycads are maintained well above the temperature of the surrounding air by heat generated internally (Seymour & Schultze-Motel 1996). The spadix of the eastern skunk cabbage, which is not frost-resistant, has held its temperature between 13 and 22°C for at least two weeks when the air temperature was between -15 and 10°C (Knutson 1974). The plant reportedly melts the surrounding snow (Seymour 1997).

Some plants enter a 'dormant' state where the metabolism, especially respiration, is slowed for survival during unsuitable growing conditions in winter. Re-growth is not possible during dormancy, even when conditions are favourable. After a period determined by the climatic conditions prevailing in the place of origin of their species, the plants are ready to grow again in the new season, usually spring. The plants are said to have been 'vernalised', the dormancy having been 'broken'. Growth will recommence when conditions are suitable (for example when the days are long enough and the temperature sufficiently high). The 'post-dormant' state following vernalisation and prior to re-growth is called 'resting' or 'quiescence'. Some seeds also pass through a dormant state.

In tropical and temperate climates many plants do not have to survive winter because they reach maturity and produce seeds in one growing season. These are the annuals such as grasses, decorative flowers and weeds. Grasses can live for more than one year, but this may not be necessary for survival of the species since seeds may be produced after only one season's growth. When the growing season is short as a result of drought or frosts, plants require more than one season to reach maturity. The annuals give way to winter annuals and biennials. Very few annual plants are found on mountains.

The biennial plants may employ a system of perennating buds and storage organs so that the drought-prone or frost-tender parts such as leaves or stalks can die in autumn, to be replaced next spring by new growth. Many vegetables are biennial plants; the storage organs

produced by the first season's growth are the major source of food for animals including man.

Trees and shrubs require several years to reach maturity and produce seeds. Deciduous trees shed their leaves in autumn and become dormant with their perennating buds freely exposed above ground. Evergreen trees have developed ways of maintaining their form through winter or drought without harm. They are of two main types, frost-tender subtropical broadleaves such as Citrus with soft succulent fruits, or frost-resistant high-altitude and high-latitude species such as Pinus whose seeds are encased in hard wooden cones. What little cold resistance the subtropical broadleaves have is merely the avoidance of freezing by super cooling a few degrees during overnight frosts. The conifers have needle-shaped leaves with thick cuticles. They harden in winter and some avoid freezing by deep super cooling, when they can withstand frosts down to -60°C. Others can actively photosynthesise at -18°C.

RAUNKIAER'S LIFE FORMS

A classification system evolved by the Danish botanist C. Raunkiaer explains how plants survive the cold of winter. It ranks plants according to the existence of perennating buds and their position relative to the ground surface.

THEROPHYTES

Therophytes have no perennating buds and rely only on seeds for survival. They are the annuals that avoid drought and frost damage by living for only one growing season. The seeds fall to the ground when the plant dies and lie on the surface until the next suitable growing season.

Seeds combine a bud and food store in one enclosure, a hard dry shell or husk. They are largely dehydrated and can usually avoid frost damage by super cooling. They may be surrounded by ice but the protoplasm of the cells will be unfrozen and undamaged.

The seeds of some plants originating at low latitude will germinate and grow immediately after ripening and drying of the seed coat. They may not necessarily be frost tolerant and may need to be stored in a safe warm place for spring or hothouse sowing if grown in temperate latitudes. The seeds of plants native to cooler temperate latitude, where growth stops over winter, may contain inhibitors to ensure dormancy until conditions are suitable for growth.

Dormancy may occur at a very early stage in the growth of a plant. The seeds of the winter annuals such as Petkus rye or winter wheat normally germinate in autumn and the small plants become dormant over winter. The plants grow to maturity and flower the next growing season. Plants grown from spring-sown seed will not mature in one season because they have not been subjected to cold weather.

The traditional autumn sowing of winter wheat in Russia was a very hazardous practice because winter losses were often unacceptably high. The technique of chilling moistened wheat seed to a temperature between 0 and 5°C for about two weeks and then keeping it in stores over winter, to be sown in spring, was successfully developed in Russia in 1928. The process was called 'jarovisation' which could be translated into English as 'Springisation'. It implied that the wheat was converted from a winter annual to a normal annual, but the seed was merely 'vernalised' artificially so that the crop bolted to seed in the first growing season. Other seeds such as those of Petkus rye have also been successfully vernalised by

cold treatment (Searle 1973), (Wang & Ray 1984), (Salisbury & Ross 1969). Commercially grown flower plants are also successfully vernalised by cold treatment to hasten flowering.

CRYPTOPHYTES

Cryptophytes avoid frost damage when the aboveground parts die off completely over winter while the buds survive below the soil surface. The underground stems (stolons) and roots containing the food required for new growth may take several forms, such as tubers (potatoes), rhizomes (irises), corms (gladioli), or bulbs (daffodils).

A surprising feature of some cryptophytes such as snowdrops and crocuses is that they flower in midwinter in mid latitudes. It has been suggested that they do this because they are native to high altitude where the growing season is very short, maybe as little as two months. It is not uncommon for alpine plants to flower precociously before the winter snow has melted. A possibility for the early and speedy growth of some cryptophytic flowers native to Britain is that they developed under deciduous forests where there was only sufficient light for growth in late winter before the trees came into leaf (Searle 1973).

HEMICRYPTOPHYTES

Hemicryptophytes may avoid frost damage when the tops die off and buds develop just above or just below the soil surface. They are often biennials such as onions or carrots. The biennials normally germinate in spring, producing a food store in the first growing season. They become dormant for winter; following vernalisation they bolt to flower the next spring. Many hemicryptophytes tend to bolt to seed in the first season without going through the stage of building up a food store.

Bolting happens when seeds are sown too early in winter or spring. Vernalisation takes place in a comparatively short time and the plants mistake the warmer weather for the second growing season, often with disastrous results. Half the carrot crop in Ohakune, New Zealand bolted to seed by Christmas in 1986 because a cold spell in spring satisfied the vernalisation requirement of the tiny seedlings. A series of field experiments at Pukekohe, New Zealand, from 1981 to 1983 shows that sowing onions too early in winter increases the incidence of bolting. More plants bolted in the coldest season than in the other two years. Bolting was also more prevalent in crops that emerged before the period of coldest temperature in midwinter, suggesting that the plants needed to attain a critical size before they were receptive to the bolting stimulus. The conclusion was that for maximum market yield sowing should be delayed until about mid June (Hutton & Wilson 1986).

The bolting of beet in their first season, with flowering in the autumn, is the result of prolonged cool days in spring. Some beets are responsive to low temperature at a very early stage of development, with no more than three adult leaves formed (Berrie 1977).

Interpollination of sugar beet crops from easy-bolting and wild species occurs in many countries, including Belgium, France and Britain. Growing crops from infested seeds results in ‘weed beet’, with increased bolting and reduced yields. The pollen from the undesirable wild beet growing near the coast is possibly carried inland to the cultivated crops by the sea breezes common in these areas (Simpson 1994).

CHAMAEPHYTES

Chamaephytes develop buds on low-growing branches where the closeness of the soil surface may still offer some protection from cold or drought. Alpine plants are commonly chamaephytic or hemicryptophytic, relying on a covering of dead and dying foliage and snow to protect the buds from frost. The temperature below 500mm of snow on a mountain can easily be -1˚C when the air temperature is -17˚C.The leaves surrounding a Lobelia bud may form a reservoir that holds enough liquid exuded by the plant to completely cover the bud. In a frost if only some of the liquid freezes then the bud will be undamaged.

PHANEROPHYTES

Phanerophytes are the deciduous trees and shrubs that have their buds freely exposed on frost-hardy woody stems and branches raised above the soil. Shedding of the leaves of the deciduous trees of the Northern Hemisphere is believed to be necessary to prevent dehydration during the dry cold winters, rather than being a device to prevent frost damage. The buds avoid frost damage by super cooling, as do the phloem cells. The xylem passages and intercellular spaces may remain frozen for long periods without damage.

CLIMATE CHANGE AND PLANT DISTRIBUTION

Mid latitude isotherms will on average move pole wards by 100 to 200km for a 1˚C global warming, moving the optimum habitat for many mid latitude species a similar distance. Alternatively, in a given region the optimum habitat may move 100 to 150m higher above sea level when the average temperature rises 1˚C.

A surprisingly small change in average annual temperature will be sufficient to determine whether or not a particular plant species will survive in its present location; a change of only 1˚C can be more than many plants will tolerate. If the average temperature at a given location rises just 1˚C the frosts causing crop damage may on average be one degree less severe. The frost-free season may increase by ten days in continental climates and up to thirty days in lowland oceanic areas. A 1˚C rise in average summer or autumn temperature can change orchard crop harvesting dates by ten days. Winter 1˚C warmer than optimum may halve flower initiation and reduce tree crop yield by 40% (Bieleski Undated). Frost damage would become less of a problem to crops growing at their low temperature limit if temperatures rise 1˚C, but inadequate chilling may begin to reduce the productivity of crops growing near their winter high temperature limit. Economic considerations would eventually force a gradual drift of cropping pole wards or to higher ground. Frost fighting equipment in a particular orchard may eventually become unnecessary through lack of damaging frosts.

A warming of 1˚C in 40 years is an order of magnitude (ten times) faster than the long-term changes in the past and is thought to be capable of widespread and drastic consequences for agriculture and horticulture. It is believed to cause acceptable growing regions to move faster than most plants and trees can migrate naturally. Some species could become marooned in an inhospitable climate and many species growing at their high temperature limit may die out. Conversely, plants at their low temperature limit may die out if subjected to a sudden and prolonged cooling of 1˚C (Hansen et al 1988). The cover and abundance of vascular plants on mountain summits exceeding 3,000m in Austria and Switzerland in 1992 has been compared with historical records. Upwards movement of species at a maximum rate of 4m per decade was observed to have occurred over the period of about 70 to 90 years

prior to 1992, during which time the mean annual temperature in Austria increased by 0.7°C (Grabherr et al 1994).

The inability of staple plants such as wheat to succeed in warmer or colder habitats will be one of the greatest problems if significant climate change occurs. The widespread development and use of cultivars with uniform characteristics reduces the genetic pool and strains that may have been able to survive the changing climate may be lost before the change occurs. Wheat, the most abundant food crop on earth, is frost sensitive and major losses have resulted from frost damage in recent times. The inability of a particular wheat cultivar to survive the winter cold in the Ukraine in 1972 resulted in the loss of millions of tons of the famous variety 'Bezostaja' that had been introduced to the area during a period of mild winters prior to 1972 (Sattaur 1989).

It has been suggested that 'rigid' cultures may have failed when they did not adjust to climate change. The Viking settlements in Greenland failed by 1500AD because they apparently relied on grazing cattle on vegetation that succumbed to the falling temperature, overgrazing and soil erosion.

COLD SPELLS AND PLANT DAMAGE

On occasion a 'cold spell', with sub-zero temperature for a few days, causes widespread damage to plants. It usually results when a large mass of polar air spreads over a wide area. In North America the cold winds that destroyed the Citrus trees in the Rio Grande Valley in 1949, 1951 and 1962 are called 'Blue Northers' (Hensz 1969).

The killing frosts that struck New England in June, July and August 1816, following the April 1815 explosion of Mount Tambora in Indonesia, killed all but the hardiest of crops. The Philadelphia Society for the Promotion of Agriculture called for facts to explain the extraordinary season of 1816, "Particularly the effects of Frost on vegetation." From the Connecticut Society of Agriculture came the reply, "The principal injury done by early and late frosts fell on our most important crop, Indian corn. Of this, there is not more than half the usual quantity." Wheat and rye on the other hand apparently yielded particularly well. This was attributed to the longer time than usual in filling and ripening. In Europe "1816 was unusually cold, dry and unpleasant" and a severe shortage of food resulted. The shortage of wheat in Europe and the failure of the American corn crops doubled the price of wheat in early 1817. In France, import duties on grain were suspended in an effort to relieve the famine and grain carts had to be given military protection.

The Royal Horticultural Society has published surveys of plant damage caused by exceptional cold spells since 1838. The 'Frost Report' of 1887 tells how mature apple, oak and walnut trees were killed in December 1879. The cold spells that struck Britain in December 1981 and January 1982 gave minimum temperatures between -14°C and -16°C, -15°C and -19°C respectively. The damage to mature trees and shrubs was remarkable. Many varieties such as cedar, fig, Leylandii, Magnolia, pine, Camellia and Rhododendron were killed or badly injured. Furze, holly, ivy and rose suffered severe damage in the coldest parts of the country. Eucalyptus, Eucryphia, Hebe and Pittosporum died in many places (Burroughs 1984).

The relative frost susceptibility of cultivars was responsible for the changed apple eating habits of North Americans during the great depression in the nineteen thirties. In New York State 2.5 million apple trees were killed in a freeze that virtually destroyed the preferred 'Baldwin' cultivar, but 98% of the 'McIntosh' variety survived, eventually replacing the Baldwin (Kavaler 1972).

The frosts around the Mediterranean Sea in January 1985 caused widespread crop damage in Southern France and Italy, where the temperature ranged from -22˚C for over a week at Pistoia, to -7˚C in the South. Even plants inside greenhouses were damaged (Hort. Abstr., 1986, 412). The temperature went below zero for ten successive days in Corsica and reached -6˚C. Top growth on some avocado cultivars was killed, along with many passion fruit and pitanga plants. Male and female flowers of two- to five-years-old jojoba plants were killed, but stems and leaves were undamaged. Kiwifruit, feijoa, loquat and carya were not damaged (Hort. Abstr., 1986, 4620). In the lower Rhone Valley and Roussillon, France, lettuce, endive, carrot, globe artichoke, fennel, Swiss chard and spinach were severely damaged or destroyed, but there was little damage to asparagus, onion and garlic (Hort. Abstr., 1986, 5957).

A common feature with widespread cold spells is that species introduced from milder climates may be damaged much more extensively than native varieties. In the 1981-82 cold spell in Britain, many Ceanothus, tree heather, Spanish broom and strawberry trees from the Northern Hemisphere, and Eucalyptus, Eucryphia, Hebe, and Pittosporum from the Southern Hemisphere, were killed. Acacia and Eucalyptus were fairly severely damaged in the 1985 freeze in France (Hort. Abstr., 1986, 5808). Severe frosts occurred in Central Otago, New Zealand in early winter 1988, with record low screen and grass minimum temperatures established in many places. Pinus radiata trees twelve to fifteen years old were killed and well established Eucalyptus and Acacia were damaged by frost (Manning 1991).

GROWING SEASON

Plants are usually at most risk from frosts in spring and autumn when the average monthly screen minimum temperature is a few degrees below freezing. The last killing frosts in spring and the first in autumn (air temperature falling below -2deg.C) define the beginning and end of the growing season. Frost damage is likely to be a problem to any plant requiring a longer growing season than is available, when killing frosts occur later in spring or earlier in autumn than usual, or when the frosts are colder than the plants can tolerate during the growing season. The growing season changes by between a fortnight and a month for a one degree Celsius change in mean annual temperature (Ford 1982). The growing season in the English Lowlands was three to four weeks shorter during the Little Ice Age than in the mid twentieth century.

Temperature generally falls as elevation rises. Frost risk increases and the growing season shortens. It has been said that American Indians advised European settlers not to plant corn until the white oak, elm and hickory leaves in the hills, and Osage orange leaves on the plains, were as big as squirrels' ears. Mean temperature rises about 0.6˚C/week in mid latitude spring and temperature falls about 0.4˚C/100m of altitude. Assuming similar rates of change in autumn the growing season would change by about nine days if the altitude changes by 100m. This is consistent with the observed shortening of the growing season in Eastern USA by five days, in the European Alps by six and in Scotland by twelve when altitude is increased by 100m. The manmade heat in the City of London markedly increases the growing season; pears blossom three weeks earlier than in a country garden only 80km away (Johnson 1973).

FROST HARDINESS

Freezing injury occurs when plant cell membranes are ruptured by ice and the cell vacuole freezes. Freezing outside the cell and in the cell wall matrix can usually be tolerated but membrane rupture and vacuole ice may be fatal.

The frost resistance or hardiness of new growth, fruiting wood, new buds, flowers and fruit is minimal. Spring, summer and autumn frost damage occurs because growing tissue is not frost hardy. Tissue ice nearly always injures all parts of plants in summer, but many plants become resistant to frost damage as winter approaches, returning to a frost-tender state in spring. Winter frost damage is usually the result of inadequate hardening of dormant material.

Hardiness increases as plants enter their dormant state, following the slowing or cessation of growth in autumn. Hardening starts with young shoots and buds, then moves down the plants to the trunks, but the roots harden little. The hardening process is called 'acclimation', defined as a natural physiological adjustment to a changing environment, a natural acclimatisation not imposed by man. This contrasts with 'acclimatisation', which is evoked by human agents.

A major metabolic change that may contribute to hardening is the conversion of starches to sugars in plant tissues in autumn with the reverse change in spring. There is also an increase in water-soluble proteins in many species as they harden. This too may contribute to increased hardiness.

Structural changes in plant cell membranes are believed to occur during hardening so that they offer virtually no resistance to water movement. This reduces the likelihood of ice forming within the cells, increasing the probability of survival during a frost.

There is usually little risk of frost damage to dormant deciduous tree buds. Peach flower buds are killed at about -26˚C in winter but when they begin to expand in spring they rapidly lose hardiness. Like other pip fruit and stone fruit buds they are damaged at about -6˚C when swelling and at about -4˚C when petals begin to show. At full bloom -3 to -2˚C damages buds, while small fruits are damaged just above -2˚C.

INADEQUATE ACCLIMATION

Properly acclimated plants will survive a normal winter without frost damage. Frost can however severely damage inadequately hardened plants with resultant loss of production and even plant death. Plants from warm climates or those growing at the cold limit of their range may be unable to acclimate sufficiently to escape frost damage. They may be susceptible to frost because they fail to develop sufficient hardiness, do not harden rapidly enough for protection from cold weather in autumn, or de-harden too rapidly to survive a late frost in spring.

Dormancy is not well developed in subtropical evergreens and growth can occur at any time of year. Hardiness does increase in winter however and offers limited frost protection. Citrus wood and leaves acclimate slightly but fruits do not. Citrus fruits may super cool to a limited extent. Immature fruit freezes at about -1˚C and mature fruit freezes near -3˚C. In both cases internal ice injures the fruit. Large fruits can tolerate frost better than small because their large mass slows the cooling rate. Non-hardy leaves survive to about -4˚C and acclimated leaves are killed at -9˚C.

Winter damage to Citrus depends on the climate. Where the winters are warmer, as in Florida, USA whole trees must be saved but in California, with cooler winters, only the fruit requires protection. This apparently anomalous phenomenon is a result of the better acclimation of the trees grown in the colder region (Weiser et al 1979).

INADEQUATE WINTER CHILLING

Problems may arise when the climatic requirements of a plant are not met during the dormant season. A minimum sustained winter chilling period of say six weeks with mean daily

temperature below 7˚C may be necessary to break dormancy. Then a 'photo periodic' requirement must be met, followed by a minimum period of warmer weather before resting is complete and growth recommences in spring.

The approximate winter chilling requirements for many species of economically important plants are well known and they may be used as a guide when deciding the suitability of the species for a particular location. Between 500 and 1,500 chill units are typically required for deciduous fruit trees, but the simple idea that chilling requirement can be met by a large number of hours below 7˚C is likely to be insufficient for some species. The Utah Chill Unit model that gives 'Richardson Chill Units' assumes that the effective temperatures lie between 1.4 and 14˚C with most effect at 6˚C. This too may be inadequate (Wilton 1988). The duration of chilling temperature below 7.2˚C in California, USA during winter is about 300 hours at sea level and typically increases to about 700 hours at 1.5km elevation at an average rate of some twenty-seven hours per hundred metres (16min/m) (Aron 1983).

Frost is a necessary but not sufficient ingredient of winter chilling; the high daytime temperatures reached during fine frosty weather may actually reduce chilling. Plantings on south-facing slopes in the Southern Hemisphere experience better chilling than those facing the Sun. Experience in California, USA has shown that the chilling requirement of trees in the shade is satisfied earlier than those in the Sun and that bud break can be better after cloudy winters (Aron 1983). East-facing slopes induce better chilling than westerly ones because evaporation of dew reduces the heating effect of early morning sunshine. The afternoon sun warms westerly slopes; they stay warmer overnight and less dew forms. Plants on northwest slopes in the Southern Hemisphere may suffer trunk burn in winter due to high daytime temperature followed by cold night.

Many peach trees have been killed in southeast USA by frost following a warm spell in late winter, after their chilling requirements have been met. The trunk, crotch and larger branches of frost-damaged trees show browning of the cambium, phloem and occasionally xylem tissues. Damage usually occurs when air temperature falls to about -4˚C to -6˚C for a few days following several days with daytime air temperature between 16˚C and 26˚C (Savage 1970).

The range of mean winter temperature between too warm and too cold may be only a few degrees for most plants. The bud burst and flowering of Kiwifruit in New Zealand shows this. The mean monthly screen temperature in midwinter in Northland (10˚C) is some three degrees higher than in Nelson (7˚C), yet Kiwifruit reach 'bud burst open cluster' a fortnight later and '50% flowering' only four days earlier in the North (Morley-Bunker & Salinger 1987). The 1987 Kiwifruit bumper harvest in Northland was believed to be due to the unusually cold winter in 1986 resulting in even bud break and flowering. The temperature in the 1986 winter was about 1˚C below normal and in the spring about 1˚C above normal (NZ & SH 1987). The colder winters in Nelson are thought to result in better Kiwifruit growth than in the Bay of Plenty but frost damage in Nelson is about four times more likely. Frost fighting is often required in Nelson but rarely used in the Bay of Plenty where average minimum temperatures are about 2˚C warmer.

Winter and spring temperatures control bud burst and flower development of some deciduous species, depending on their chilling requirements. As a rule three possibilities exist:

(1) Warm winter and spring will result in insufficient chilling to break dormancy. There may be late and erratic bud burst and rapid flower development. In extreme cases peach and apricot trees may lose 90 to 100% of their flower buds, the remainder may be smaller than normal, deformed or the anthers fail to dehisce. Leaves may be few and small and develop irregularly.

(2) Optimum winter and spring temperatures will match the chilling requirements, giving uniform early bud break, good flower development and maximum crop yield.

(3) Cold winter will satisfy dormancy requirements early but frost risk in a cold spring will be high, especially if a short warm spell occurs in early spring and allows growth to start too soon. Flowering may be delayed so much that the crop does not reach maturity before the next winter.

CHAPTER FOUR

FREEZING OF PLANT MATERIAL

INTRODUCTION

Plant cells have ice barriers that give plants a natural resistance to frost damage. As a rule frost damages plants only when the ice formed within their tissues damages the barriers in the cell walls and membranes. Plant surfaces must cool below 0˚C before ice can be nucleated and grow on them. Ice often appears on plant surfaces at about -2˚C but cooling may sometimes go as low as -15˚C before nucleation starts. With few if any exceptions frost ice forms first on plant surfaces and propagates through the stomata or other holes in the surface into the extra-cellular spaces.

Frost injury often resembles drought damage, the result of dehydration rather than the presence of ice within the plant cells. Survival requires freezing and thawing to occur gradually. Plants that are frozen or thawed too quickly may be damaged because water has not been able to move through cell walls quickly enough.

ICE GROWTH IN PLANTS

Frost ice in plants is always nucleated heterogeneously by suitable microscopic particles present on their surfaces. The nucleating particles of interest may be expected to have radii of curvature between 2.4 and 20nm (nanometres). It appears that frost ice may be nucleated by either very small inorganic particles such as clay, effective below -10˚C, some unknown (in 1988) feature of the woody stems of Prunus, or proteins associated with bacteria such as Pseudomonas syringae, P. fluorescens or Erwinia herbicola, effective at -2˚C (Schnell & Vali 1972), (Vali et al 1976).

Damage to plants is sometimes avoided in light frosts when ice fails to nucleate on their surfaces. Whole plants may then super cool a few degrees and remain unfrozen for the duration of the frost. Potatoes, wheat and Citrus sometimes escape frost injury by super cooling. Super cooling is sometimes made use of for frost protection. Shortly before an expected frost the particles that would nucleate the ice are removed, or are prevented from being present, on the plant surfaces.

Super cooling before ice nucleation on plants is more likely to occur during black frosts than when the humidity is high. It has been found to be greatest on apricot blossoms on still, dry nights when there was no dew visible on the petals (Atkinson 1952). In the absence of rain, evaporation causes plant surfaces to remain dry during a frost until they have cooled at least to the dew point (above 0˚C) or the frost point (below 0˚C), depending on the absolute humidity of the air. Dew or frost will appear on a surface that has super cooled below the dew point or frost point only when there are a sufficient number of appropriate nucleating particles present on the surface.

Super cooling occurred before ice nucleation on Eucalyptus leaves as the leaves cooled overnight in a radiation frost at Canberra, Australia. The recorded temperatures are shown in Figure 4.1 (Leuning & Cremer 1988). The sudden temperature rise from -2˚C to -0.2˚C for a large leaf at about 2330 and the similar event when the small leaf warmed from -1.5˚C a few minutes after midnight appear to be the result of nucleation of super cooled dew or subliming water vapour.

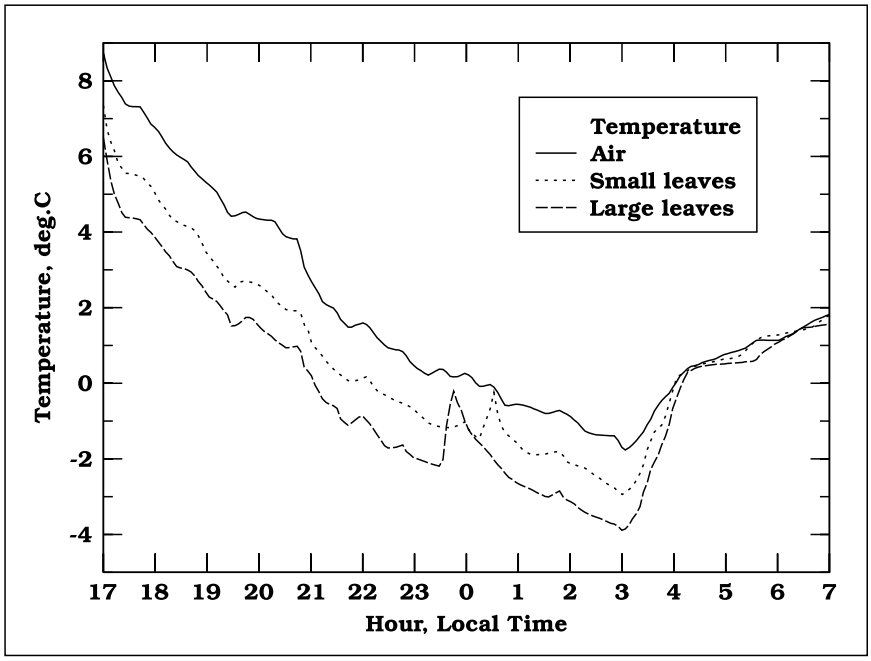

FIGURE 4.1. Temperature of the air, small and large eucalyptus leaves 40mm above moist soil in a radiation frost, showing the effect of the onset of ice nucleation about midnight and the incursion of radiation fog about 3am. (After Leuning and Cremer).

SURFACE ICE BARRIERS

The external surface of the epidermis or skin of a plant is sometimes covered in a non-cellular cuticle or waxy waterproof layer. The dew and frost on such waxy plant surfaces is often a collection of minute droplets or crystals, with areas of dry surface between, as seen in Plate 4.1. The only way for this surface ice to nucleate the water within the plant is for ice to cover a stoma, lenticel, pore, or wound connecting to the extra cellular and intercellular spaces. The chance of this happening is increased when the plant is wet following heavy dew or overnight rain, as a result of overhead irrigation, or due to water sprinkling used for crop protection.

PLANT CELL ICE BARRIERS

The structure of live plant cells is similar to that shown schematically in Figure 4.2 (Goodwin & Mercer 1983). Literally thousands of observations have failed to show ice anywhere but in the extra-cellular spaces of naturally frozen and undamaged plant tissues (Salisbury & Ross 1969). Ice grows only so long as the temperature of the ice front can be kept below the freezing point. Porous or water-permeable materials are effective barriers to ice growth because the freezing point in small pores is depressed below that in bulk water. The water must be cooled below the freezing point in the pores before ice can grow through the barrier. There are two porous barriers to ice growth in plant cells that may confer a significant

degree of frost protection. The first barrier is the strong cellulose container or cell wall that prevents the cell being ruptured by the outwards turgor pressure of tens of atmospheres resulting from osmosis. (Cell walls also form the skeleton or framework of a plant.) The second barrier, the plasma lemma, lining the inner side of the cell wall, is a lipid bilayer membrane that encloses the cell contents. Ice can be tolerated around and between the cells of frost hardy plants, but if ice penetrates through the plasma lemma membranes into living cells they may be killed, or at least badly damaged.

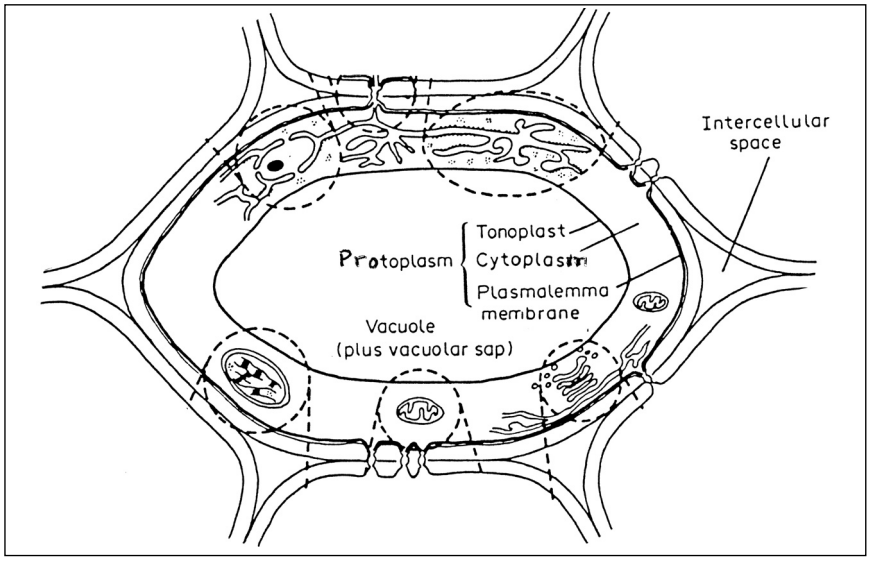

FIGURE 4.2. Schematic diagram of the structure of a metabolically-active mature plant cell. The cell wall is lined with the plasma lemma that completely surrounds the protoplasm and other cell contents. (After Goodwin & Mercer).

CELL WALLS

Walls of mature plant cells are typically composed of two layers, the primary (outer) and secondary (inner). Primary wall layers are a very thin and pliable matrix or mesh about 60nm thick, composed of cellulose micro fibrils, each fibril about 5 to 15nm radius and 10um long. Interstices between the micro fibrils of the primary wall layers are comparatively large and porous, filled with a mixture of water and hemicelluloses. The secondary wall layers are up to about 3um thick. The cell wall matrix is then seen to be an effective barrier to ice growth from the extra cellular spaces into the living protoplasm. Assuming an effective pore radius for primary wall layers of say 5nm, the unfrozen water in the pores will not be nucleated by ice above -6˚C and for secondary wall layers with 2nm radius pores the barrier will be effective down to at least -15˚C.

The protoplasm of adjacent live cells may be joined through small holes in the cell walls. These holes or plasmodesmata typically have radii of 10 to 100nm and they allow free passage of water and small solutes between adjacent cells. Presumably ice will not grow through the plasmodesmata from a frozen cell into an adjoining unfrozen cell at temperatures above about -3˚C.

In dead wood cells (xylem) devoid of protoplasm the holes in the walls joining adjacent cells are known as pits. The pits are of similar size to plasmodesmata, so ice will not propagate between cells at temperatures above about -3˚C.

CELL MEMBRANES

A lipid bilayer membrane about 8nm thick, the ectoplast or plasma lemma, lines the inner surface of the cell wall. In a living cell the plasma lemma separating the cytoplasm and the cell wall is a very effective barrier to large molecules. It is the osmotic membrane and coincidentally the second barrier to ice nucleation within the cell. The 'holes' in the plasma lemma are so small that ice cannot grow through them to nucleate the cell sap at any temperature above the homogeneous nucleation temperature (-38.1˚C). Water-soluble molecules cannot easily pass through the bilayer, but may sometimes be able to pass through proteins that are deeply embedded in the membrane, either through a hydrophilic channel or a passive hole. Metal ions such as sodium and potassium may also be preferentially passed while others are blocked.

The cell space enclosed by the plasma lemma contains a similar membrane called the tonoplast that surrounds at least one sac or vacuole containing the cell sap, an aqueous solution of salts, sugars, proteins and pigments. Between the tonoplast and plasma lemma membranes is the cytoplasm, a viscous aqueous fluid. The freezing point of the cytoplasm is the same as that of the vacuole, in the region of -0.5˚C to -4˚C.

The vacuolar space may be divided into several compartments, the number of sacs changing from time to time. It appears that a single vacuole is often a feature of summer, while multiple sacs appear in autumn as the plant hardens. It is believed that multiple vacuoles are an effective way of reducing winter frost damage when ice forms in plant tissues. In spring, as the plant de-hardens, the cytoplasm may be rearranged into a single vacuole. These seasonal changes are shown in the photomicrographs of Plate 4.2 (Wisniewski & Ashworth 1986). The only way for ice to form within the cytoplasm or vacuole during a frost seems to be for the plasma lemma to be ruptured, allowing extra-cellular ice to nucleate the sap.

The ice barriers of the cell wall matrix and plasma lemma are apparently so effective that intracellular freezing is abnormal and does not generally occur in nature. It is believed however, that intracellular freezing may cause sunscald injury to trunks in winter and the winter killing of barley (Levitt 1972).

Nucleation of the extra-cellular spaces of some tissues by external ice is sometimes prevented by barriers such as the zone of relatively undifferentiated cells found between primordial flower buds and normal stem tissues. Ice may form in the stem but the dormant over-wintering flower buds remain unfrozen and super cooled. The buds of plants such as blueberry, apricot, peach, Azalea, cherry and plum are capable of deep super cooling. The primordial flowers of peach have been known to have super cooled to -25˚C and Azalea buds have remained unfrozen at -40˚C (Burke et al 1976).

DAMAGE BY EXTRA-CELLULAR ICE

Extra-cellular ice injures non-hardy species and the non-hardy tissues of spring or summer growth of hardy plants. Hardened plants survive extra-cellular ice in winter, when the sap within some cells stays unfrozen down to perhaps -47˚C. Most deciduous forest species and fruit tree cultivars have cells that remain unfrozen in winter even though they are surrounded by extra-cellular ice.

Frost damage may result from cell dehydration by reverse osmosis when the solute concentration of the extra-cellular fluid increases as ice builds up. Osmosis is the process where water normally flows in through the plasma lemma from the weaker solution outside the cells to the cytoplasm and vacuole, where the solute concentration is normally highest. The plasma lemma is pushed hard against the inside surface of the cell wall matrix by a 'turgor' pressure of tens of atmospheres in typical land plants and up to 132 atmospheres in halophytes such as mangroves (1 atmosphere = 101,325Pa).

As cooling continues the growing ice will remove enough water for the extra-cellular solute concentration to exceed that of the cytoplasm and vacuole. Reverse osmosis starts and the cells begin to dehydrate. The periplasm or space between plasma lemma and cell wall varies according to the turgor pressure. If the osmosis reverses and the pressure reverses from outwards to inwards the plasma lemma may be pulled away from the cell wall, a normally reversible non-damaging process called plasmolysis. Survival then depends on the ability of the plasma lemma to be pulled away from the cell walls without rupturing, while shrinking to just contain the smaller volume of the partly dehydrated cytoplasm and vacuole.

Ice will not form in the space between cell wall and shrunken plasma lemma until it is nucleated by ice growing through the wall when the temperature goes below the freezing point appropriate to the largest interstice in the cell wall (possibly as high as -6˚C in new growth, depending on species). Ice in the space between plasma lemma and cell wall is shown schematically in Figure 4.3 (Marchand 1987). The plasma lemma rarely ruptures when plants are frozen slowly in a frost, but if the ice continues to grow until it ruptures the plasma lemma and triggers the nucleation of ice in the cytoplasm or vacuole, it kills the super cooled cell instantly.

An alternative mechanism for frost damage by extra-cellular ice is cytorrhysis when the temperature does not fall low enough for ice to grow through the cell wall interstices but reverse osmosis continues, lowering the sap freezing point. A point will be reached where the sap is super cooled but the ice barriers in the cell walls prevent nucleation. Further freezing may eventually reach the point where the ice barriers are no longer able to withstand the pressure exerted by the extra-cellular ice, they rupture, the cell sap comes into contact with the ice, the sap freezes and the cells are killed.

Cytorrhysis may not necessarily result in cell wall damage. It has been suggested that it is sometimes possible that cell walls contract, giving large spaces where extra cellular ice may grow without damage. The process is called 'glacier formation'; the spaces were called 'glacons' as early as 1869 (Bleasdale 1973).

DEHYDRATION DAMAGE

Cell damage during a frost does not generally appear to be due to a ruptured plasma lemma and intracellular ice. The freezing point of normal cell sap of most species of agricultural importance is usually between -0.5 and -2˚C and rarely as low as -4˚C. Dehydration by extra-cellular ice in a frost pushes the cell sap concentration towards saturation, with consequent lowering of the freezing point. Cell sap that has been dehydrated to saturation will not freeze above perhaps -10˚C, yet many plants are damaged by frost at temperatures above the freezing point of saturated cell sap. The overwhelming evidence is that the protoplasm is not damaged by intracellular ice but by dehydration, as first suggested by Muller-Thurgau in 1886. This conclusion may be drawn from the excellent agreement between frost and drought hardiness (Levitt 1956), (Steponkus 1984).

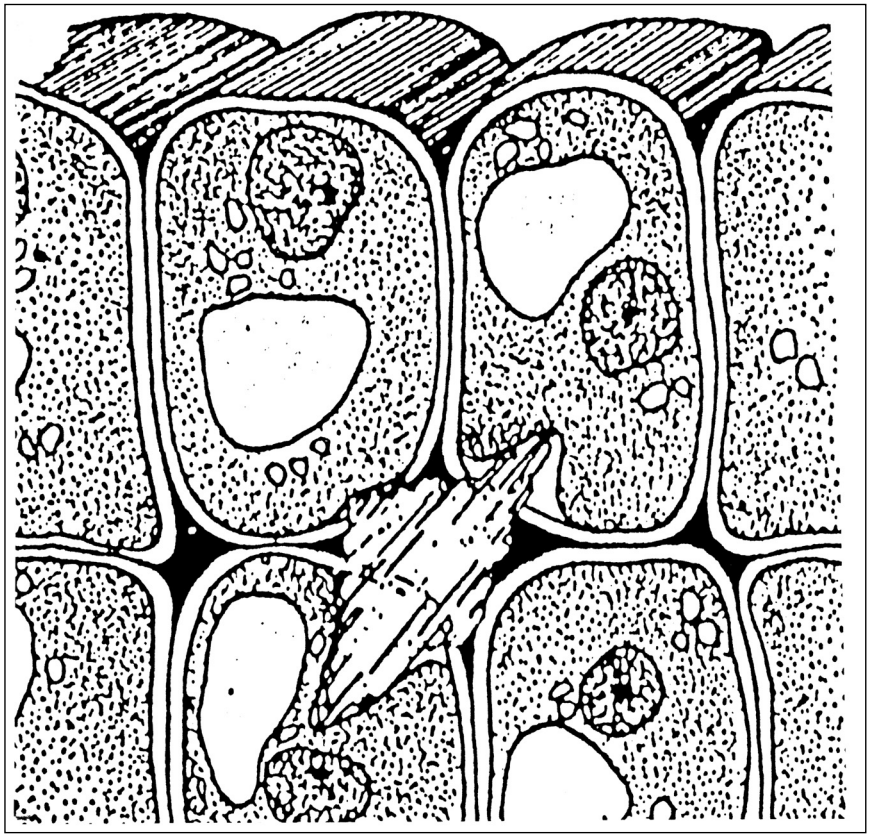

FIGURE 4.3. Schematic diagram showing ice growing in the intercellular spaces and through plant cell walls, pushing against the shrunken plasma lemma that remains intact. (After Marchand).

If it is assumed that frost damage is due to dehydration then an estimate of the frost killing temperature may be made if the dehydration causing drought damage can be established. Figure 4.4 (Levitt 1972) shows the frost killing temperature assuming that it is directly related to the killing dehydration of the cell sap. The amount of dehydration will depend inversely on the original osmotic potential and hence the original freezing point of the turgid cell sap. At a given temperature 'thin' sap is dehydrated more than 'thick'.

The following conclusions may be drawn from Figure 4.4:

(1) Freshwater aquatic plants and succulents with sap having freezing points of about -0.5˚C have little frost hardiness. If they can withstand dehydration of about 70% they may be able to survive cooling to -1.6˚C.

(2) Trees with sap having freezing points of about -2˚C may be able to tolerate -7˚C in summer, if they can withstand 70% dehydration.

(3) Plants such as wheat, rye and turnip rape, that can withstand over 80% dehydration, can easily survive -10˚C.

(4) At least 90% dehydration tolerance is necessary for plants to be able to survive winter in the boreal forests.

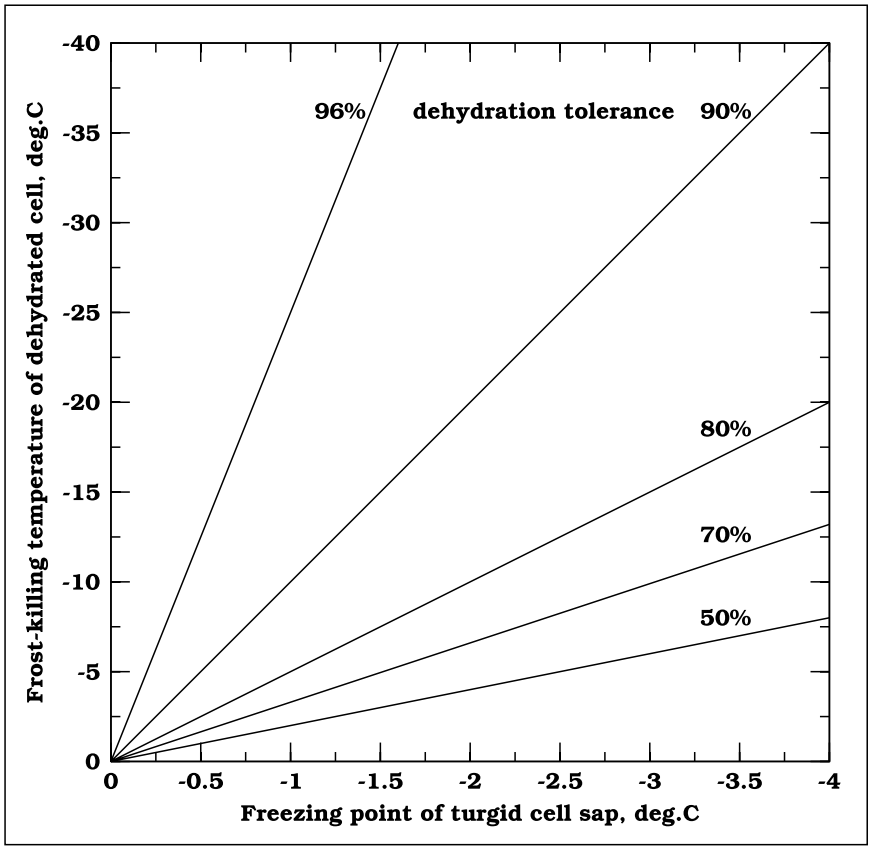

FIGURE 4.4. Frost-killing temperature of a plant cell assuming that the cell is killed as a result of dehydration by extra-cellular ice. (After Levitt).

Cells killed by dehydration are sometimes said to have suffered 'frost plasmolysis'. The protoplast is unable to re-absorb water on thawing and stays contracted. The protoplasm may be coagulated, granular, or foamy and the nucleus is coarse (Levitt 1956).

NON-EQUILIBRIUM FREEZING DAMAGE

'Non-equilibrium freezing' is said to happen when super cooled plant tissue freezes with insufficient time for water to migrate to the extra-cellular spaces before they fill with ice and the cell membranes are ruptured. Early nucleation with little super cooling and slow freezing appear to be necessary to allow cells time to dehydrate to avoid frost damage. Potatoes can super cool to -6.5˚C without damage if ice is not nucleated, but if ice forms below -1.5˚C they will be killed instantly. They can however survive freezing to -3.5˚C if not hardened and to -8.5˚C when hardened if cooled slowly enough and ice is nucleated above -1.5˚C (Rajashekar et al 1983).

The cells of some plants are able to withstand very cold temperatures and extra-cellular ice without suffering dehydration damage. The living xylem of some cold-hardy deciduous

forest species and fruit tree cultivars, native to temperate regions of North America and Asia, can withstand deep super cooling to about -40°C. Below this temperature homogeneous nucleation can occur and cause damage by freezing too quickly (George et al 1982). Deep super cooling is not yet fully explained; it may be due to the accumulation of sugars such as glucose, fructose and sucrose, and proteins known as 'dehydrins' in the cells (King 1997).

Boreal forest species that survive above the snowline can apparently dehydrate so far that their cells survive frost below -40°C. They can even withstand freezing in liquid nitrogen (-196°C), suggesting that they dehydrate so far that there is no freezable water left in the cells.

THAWING DAMAGE

Just as super cooling and rapid freezing damage plant cells, rapid thawing of frosted but undamaged tissues can be fatal. Should the Sun shine directly onto frozen plants after an overnight frost the ice may melt too quickly to allow deplasmolysis to restore the cells to normal (Bleasdale 1973). Water may leak from the extra-cellular spaces and be lost rather than being restored to the cell protoplasts. It has been observed that spraying frozen plants with water before sunrise to thaw them slowly enough for deplasmolysis to occur can prevent thawing damage.

CHAPTER FIVE

RADIATION FROST

INTRODUCTION

The common radiation frost, which sometimes damages crops, may occur overnight when the sky is clear and long wave infrared heat radiates away from the upper surface of the vegetation or other material covering the ground. The surface cools and draws heat from the air as well as from the material and ground below. A temperature inversion develops in the air, convection is suppressed and wind near the surface slows to a very low speed. Frost occurrence and severity vary from day to day and place to place. Just how much cooling occurs depends mainly on the weather at the time, particularly on atmospheric humidity, cloudiness and wind speed. The frost climate at a particular site depends on surface cover, aspect, elevation and surroundings, both natural and man-made. Severe radiation frosts in New Zealand tend to come with the clearing skies and southerly winds of an approaching anticyclone.

DAY-NIGHT TEMPERATURE CYCLES

At temperate latitudes when the sky is clear, the temperatures of the soil at the Earth's surface and of the air close to it cycle up and down daily over a range of some 10 to 20°C in response to the diurnal radiation cycle. The day to night variation of air temperature decreases with height above the ground and the variation of soil temperature decreases with depth below the surface. At a height of the order of 500 metres the diurnal variation is of the order of 4°C and little of this is due to heat exchange with the surface. It is the result of the day to night change in the radiant heat balance of the air itself. The temperature of the mid-latitude atmosphere 500m above the ground is typically between 4 and 14°C and falls above 500m at approximately 0.5 to 0.6°C/100m, day and night. The diurnal temperature variation below ground rarely extends to a depth of one metre. So the air to a height of about 500m and the ground to a depth of about 1m, are the sinks for the daytime radiant heat flow between the Sun and the surface and the sources for the overnight radiation from the surface to the sky.

The day to night range of surface temperature and the degree of overnight cooling depend on the heat capacity of the air and soil and the ease with which heat can flow through the air and below ground. Wind and turbulence permit rapid heat transfer in the air; dampness and good compaction aid heat flow in the soil. Overnight surface cooling is slow and slight when it is windy and the soil is damp. Rapid overnight surface cooling and high frost risk result from low wind speed, cold dry air, dry open soil and insulating surface layers.

TYPICAL FROST CONDITIONS

All surfaces facing the sky continually radiate long wave infrared energy day and night and would become very cold if heat was not supplied from sunlight or their surroundings. The common radiation frost that develops before morning is caused by the overnight loss of heat from the Earth's surface by long wave infrared radiation.

During daytime with the Sun shining the soil surface heats up because it receives more energy from the Sun than it radiates to the sky. The soil surface receives about 700W/m^2 maximum from solar radiation on a sunny day, it warms to perhaps 25˚C, the order of 425W/m^2 radiates towards the sky and about 295W/m^2 of this heat is radiated back from the atmosphere to the ground. The net radiation into the surface is 570W/m^2; about 70W/m^2 of this heat flows into the soil below the surface and some 500W/m^2 is transferred to the air by conduction and convection, or given up to water at the surface, causing evaporation.

When the Sun sets net radiation at the surface typically changes from downwards (negative) to upwards (positive), reaching a maximum of about 100W/m^2 (By convention heat flowing into a surface is a negative quantity and heat flowing outwards is a positive quantity). Conditions are approximately isothermal both above and below the surface about sunset, so at that time only the air and soil very close to the surface can provide the heat lost by radiation and the surface is cooled about 3 to 4˚C/h. By midnight, depending mainly on the air temperature and dew point, about 300W/m^2 is radiated towards a clear sky and about 250W/m^2 of this is radiated back from the atmosphere. The net infrared radiation is upwards from the surface to space at 50W/m^2. Cooling by midnight will be only about 0.4˚C/h because significant temperature gradients will have developed in both the air and the soil and heat is able to flow to the surface from further above and below. Heat is taken from the air above and the ground below in proportions governed by the turbulence in the air and the insulating properties of the material such as grass covering the soil. About sunrise net radiation reverses and the temperature gradients are still large, so the air warms by as much as 5˚C/h for the next few hours.

After cooling has continued for a few hours at night the upper surface of the ground or grass may become frosted. The air close to the grass surface may be cooled to within a degree of the grass temperature. The air further from the surface is not cooled so much and the air 2m above ground may be 3˚C warmer than the air at grass level while the air 10m above ground may be 5˚C warmer than that at grass level.

OBSERVED FROST STATISTICS

New Zealand has a maritime climate; the warmest stations are those right on the coast, the coolest those farthest from the sea or at greatest height. The lowest recorded screen minima for the New Zealand climatological stations show that within any province the range is of the order of 3˚C for stations less than 200m above sea level. The coldest lowland screen temperature likely in New Zealand, with the exception of stations right on the coast, lies between -2 and -8˚C. The lowest recorded screen minima in the North Island are warmer than those in the South Island by about 0.38˚C per degree of latitude. Northland frosts are 4˚C warmer than those in Southland. A two-degree air frost in July occurs once in a lifetime in Northland and several times every July in Southland (Norton 1985).

The probability of a frost occurring on any night may be deduced from long-term statistics of minimum air or grass temperatures. At least ten years' data is desired. The minimum temperature data for a one hundred year period at Lincoln, a long-established lowland meteorological station in New Zealand is shown in Figure 5.1 (Data published in tabular form by N.Z. Meteorological Service). Five commonly recorded monthly data sets are available. In order of decreasing temperature these are:

(1) Average daily screen minimum temperature.

The average of the lowest air temperatures recorded in a Stevenson screen 1.3m above ground each day during the month. About half of the readings for the month are likely to be

higher than this and half lower. All nights contribute to this statistic, not just the clear sky radiation frost examples. On those nights when rain, wind, or cloud are present for some of the time, minimum temperature will tend to occur when the sky is clear.

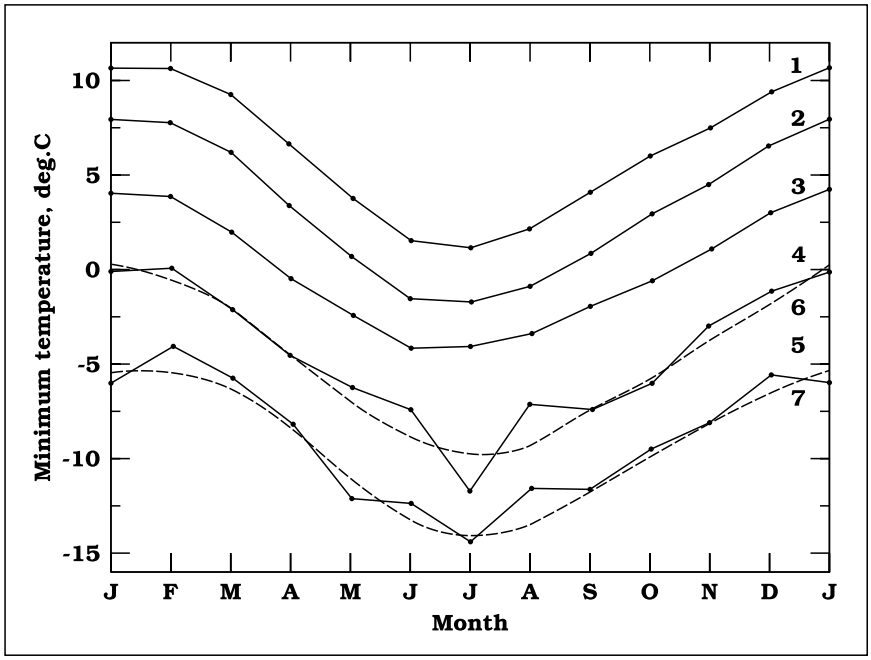

FIGURE 5.1. Minimum temperature data for a hundred year period at Lincoln. (Data previously published in tabular form by the New Zealand Meteorological Service).

1, Average daily screen minimum; 2, Average daily grass minimum; 3, Average monthly screen minimum; 4, Extreme minimum screen; 5, Extreme minimum grass; 6, "Once in a lifetime" minimum screen; 7, "Once in a lifetime" minimum grass temperature.

(2) Average daily grass minimum temperature.

The average of the daily minima in the month measured by an exposed 'grass minimum' thermometer lying horizontally 25mm above a clipped grass surface. As with screen minimum temperature, grass minimum will tend to be lowest at that time of the night when the sky is clear. About fifty per cent of nights are likely to have a higher grass minimum temperature than the average. Low-growing plants must survive this temperature.

(3) Average monthly screen minimum temperature.

The average of the lowest air temperature in each month. Only the coldest night in the month contributes to this statistic. It is the most likely minimum temperature of the coldest night of the month. The probability of this temperature being reached is 3.3% (one day in 30). Plants must be able to survive this air temperature without appreciable injury.

(4) Extreme minimum screen temperature.

The lowest air temperature recorded in single months during the long-term series. As the statistics cover a hundred years this is the coldest air temperature recorded on the coldest night of the month in 100 years. If it has not occurred more than once it may not occur again for even more than 100 years during which time the climate may have changed anyway.

The annual curve through the extreme minimum temperatures is often irregular. A smooth curve through the lowest monthly points shown dashed in Figure 5.1 for Lincoln may be a better guide to the coldest temperature to be expected in a given month. This curve may be thought of as a 'once-in-a-lifetime' minimum screen temperature prediction, or a 'hundred-year frost', with a probability of occurring once during the month of about 0.033%. Once-in-a-lifetime frosts at Lincoln are about 11˚C colder than the average daily screen minimum temperature. Frost fighting systems must be able to give adequate crop protection at the extreme minimum screen temperature if they are to be entirely satisfactory. The once-in-a-lifetime frost is so rare however that it sometimes may be considered to be a 'natural disaster' and crop damage covered by public disaster insurance.

(5) Extreme minimum grass temperature.

The lowest temperature recorded by a grass minimum thermometer in single months during the long term series. As with extreme minimum screen temperature a better estimate of the coldest ground frost likely to occur will be given by plotting a smooth annual curve through the lowest monthly points (shown by the dashed curve for Lincoln in Figure 5.1). At Lincoln this curve lies about 12˚C below the average daily grass minimum temperature curve.

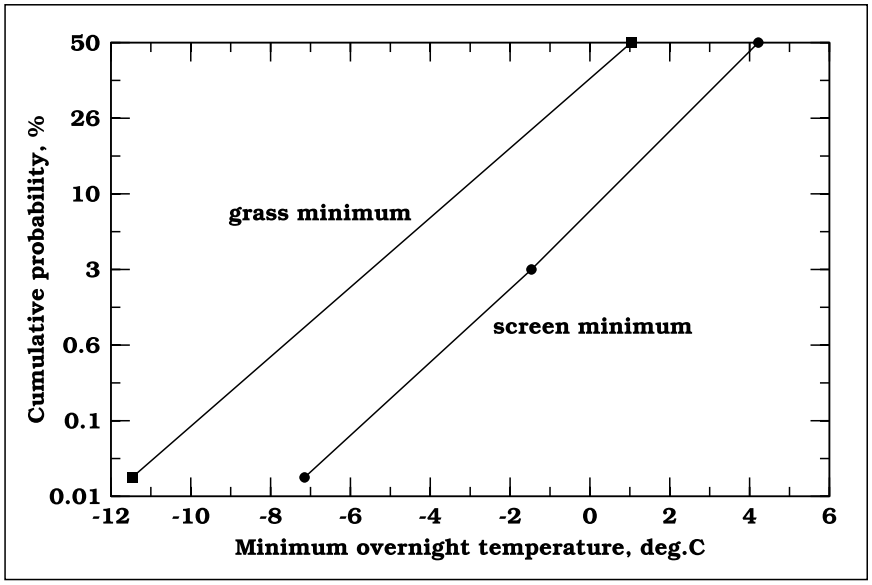

FIGURE 5.2. Cumulative probability chart for overnight minimum screen and minimum grass temperatures in September at Lincoln. (Data previously published by the New Zealand Meteorological Service).

An alternative way of showing the variability of frost temperature is to plot the data for the month of interest on a cumulative probability chart. The data for Lincoln for September are shown in Figure 5.2. This diagram suggests, for example, that minimum screen temperature in September may reach +4.2˚C fifteen times (P = 50%), is likely to reach -1.6˚C once (P = 3.3%), but will reach -7.2˚C in September only once every 100 years (P = 0.033%). Joining these points by a smooth curve gives the probability that minimum overnight screen temperature at Lincoln in September will reach a given value, say the danger temperature

for frost damage to a crop. (Had the distribution of temperature been normal the curve would have been a straight line.) The points for grass minimum temperature may also be joined by a curve to allow the probability of ground frost to be estimated. Probability changes by a factor of about two for a change of temperature of one degree near 0°C.

Averaged maximum and minimum daily air temperatures (presumably screen temperature) data for 85 years at Grand Junction, Colorado USA have been plotted in Figure 5.3 to show that the probability of a damaging frost falls from 90% to 1% over a period of 45 days as spring progresses (Doesken et al 1989). An interesting feature of these data is the scatter in extreme daily minimum temperatures; early in March it is 6°C and by May it is 3°C. Even the data collected over 85 years appear to be insufficient to allow the extreme daily minimum temperature on any day to be predictable with any certainty. As with the monthly data for Lincoln it appears that a smooth curve through the lowest extreme daily minimum temperatures would be the wisest approach to predicting the severity of a 'once in a lifetime' frost.

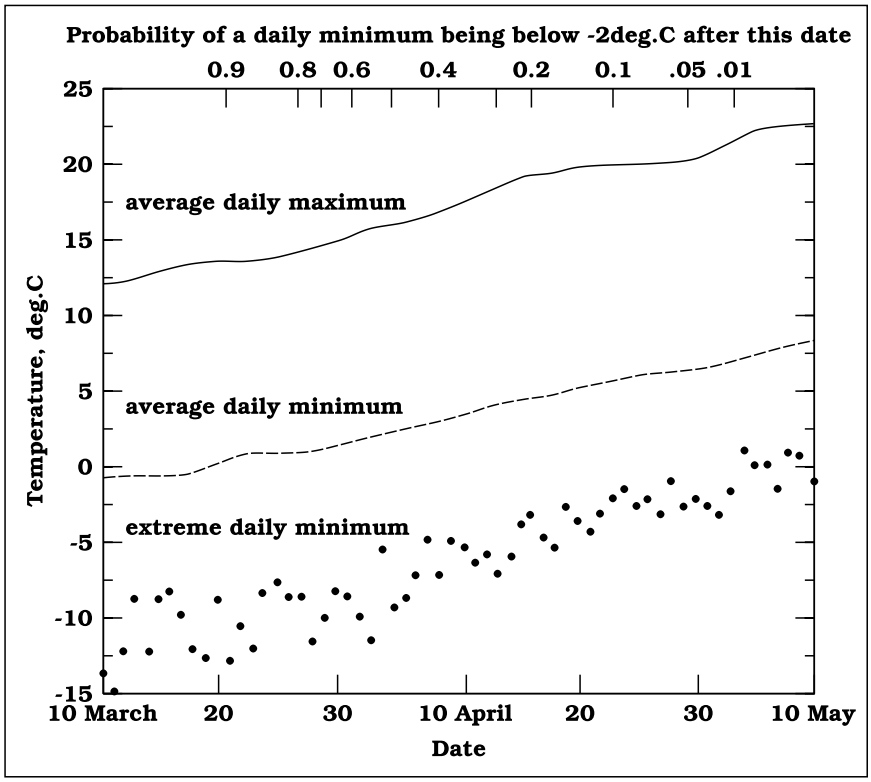

FIGURE 5.3. Spring air temperature data and -2deg.C air frost probability for an eighty five year period at Grand Junction. (After Doesken et al).

Figure 5.4 for Earnscleugh, New Zealand shows the relative occurrence of ground and air (screen) frosts as mean screen temperature changes in spring and autumn. (The mean is the average of the maximum and minimum temperatures recorded every day of the month.) There are about eight more ground frosts than screen frosts per month. Mean screen temperature changes by about four degrees per month: both ground and air frosts decrease or increase by about eight per month. For a given monthly mean screen temperature there are about two more spring frosts than autumn frosts per month.

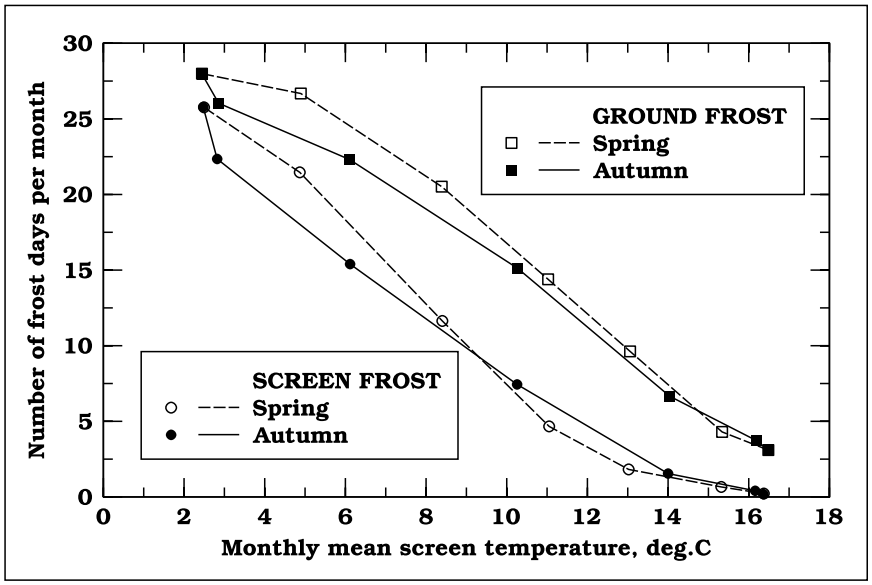

FIGURE 5.4. Relative occurrence of ground and screen frosts throughout the year at Earnscleugh. (Data from NZMS).

TEMPERATURE INVERSION BELOW SCREEN HEIGHT

The average daily screen minimum temperature curve for Lincoln lies about 3°C above the average daily grass minimum curve. The temperature inversion between the grass and the screen on clear sky nights can be expected to be at least as large as this and significantly larger in particularly severe frosts. For most lowland New Zealand meteorological stations the temperature inversion in extreme frosts appears to be of the order of 4°C. The coldest screen and grass temperatures in a month would normally occur on the same night. The temperature inversion in extreme frosts should then be shown by the difference between the lowest recorded screen and grass temperatures after fitting smooth curves to the extremes as previously suggested and as shown in Figure 5.1 for Lincoln. This shows an extreme inversion of about 4°C between air temperature at grass and screen height (25mm above short mown grass and 1.3m above ground), which is not often observed during frost research experiments. This may not be surprising, as these experiments would only by extremely good fortune coincide with very calm conditions or once-in-a-lifetime frosts. The difference between air temperature at grass and screen height is more often of the order of the 2°C observed at Lincoln in 1969-70 (Young 1971) or at Roxburgh in 1981 (Ireland 1984).

The difference between grass and screen minima at Geisenheim, Germany was averaged for the years 1937 to 1944 (Geiger 1980). In extreme cases grass minimum temperature was 6.5°C lower than the screen minimum. The temperature difference was greater for clear sky weather than when it was dull. On dull nights the air near the surface could be warmer than at screen height. Figure 5.5, from a paper by F. Witterstein (Geiger 1980), summarises the data for the occasions when the wind speed was less than 3.4m/s, giving a significant difference between grass and screen minimum temperatures. On dull nights the temperature inversion between grass and screen minima peaked at about 0.6°C, on clear nights near 2.5°C.

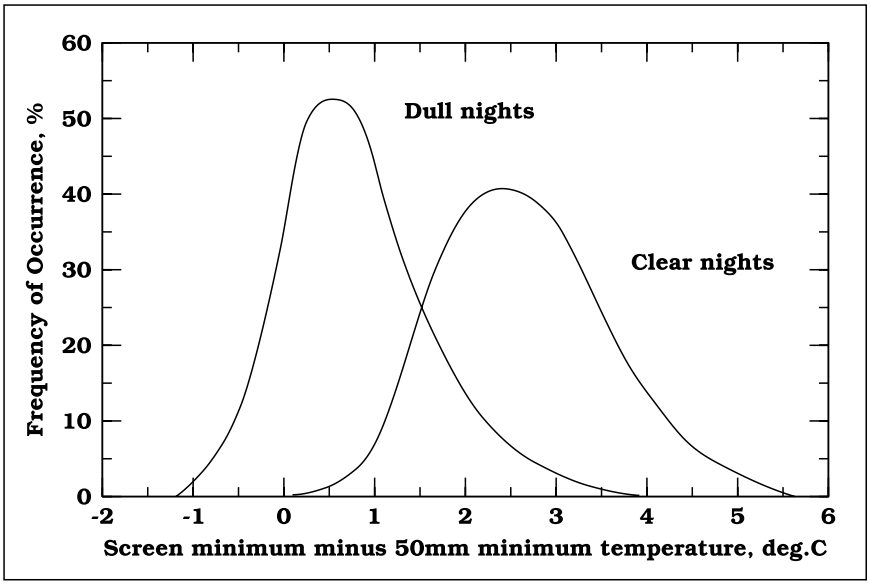

FIGURE 5.5. Frequency distribution of the difference in air temperature between screen minimum and grass minimum at Geisenheim. (After F. Witterstein).

EFFECT OF VARIABLE WEATHER

Frost incidence and severity depend on the weather. Hour to hour variability of the weather usually comes from hour to hour changes in cloudiness or wind speed. Day to day variability arises from the passage of the large-scale (anticyclone or depression) weather patterns. Year to year variability results from large-scale movement of weather patterns or from climate change. Whole months, seasons or even years can be consistently warmer or cooler than the average taken over a long period. A month one degree cooler than normal in spring or autumn may have about two more frosts of a given intensity than a normal month.

A major contributor to the variability of frosts is the change of the weather from day to day. The temperature some 500mm below the surface of the ground changes little from day to night and even from month to month. The maximum daytime screen temperature in New Zealand, for example, may vary + or -7°C in September and the likelihood of a radiation frost is largely dependent on the air temperature and humidity at the onset of temperature inversion about sunset.

Frost severity depends on hour-to-hour weather changes. This was clearly shown by a series of measurements in a large open site (a newly-established apricot orchard) at Roxburgh, New Zealand in spring 1981 (Ireland 1984). The curves of Figure 5.6 are smoothed averages of the screen temperature recorded on at least six nights in each category over a two-month period.

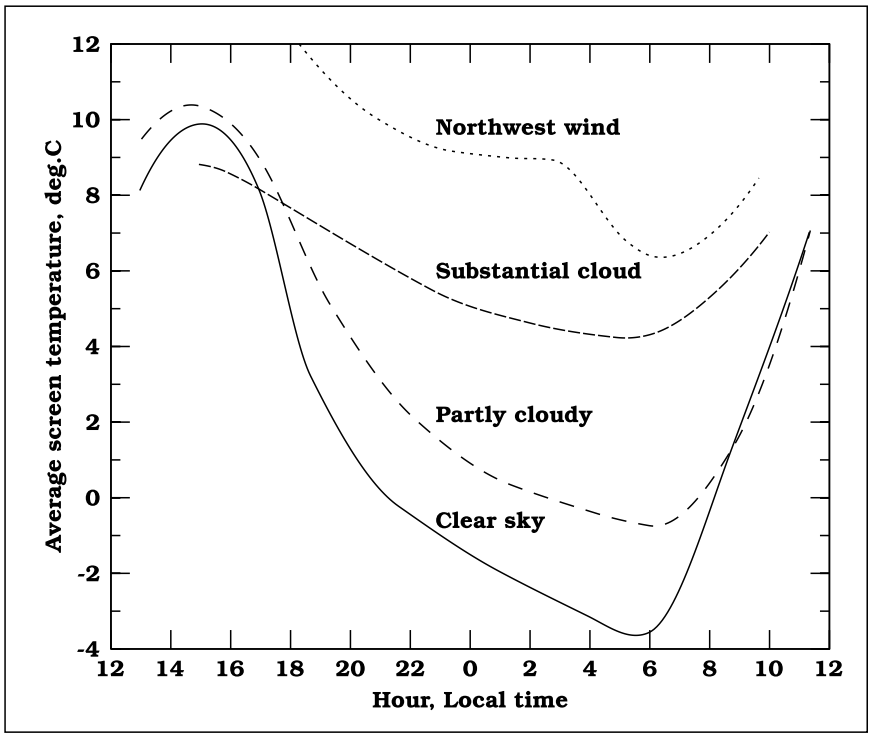

FIGURE 5.6. Smoothed averages of screen temperature recorded on at least six nights in each category over a two-month period at Roxburgh in Spring 1981.

The effects of variable weather observed at Roxburgh were:

(1) Clear sky, low wind speed.

Screen temperature fell thirteen degrees from 10˚C in the afternoon to a -3˚C minimum just before sunrise. Maximum cooling rate was 3˚C/h after sunset, minimum 0.35˚C/h before sunrise. The temperature inversion between 1.3 and 20m was typically 1.6˚C. Frost penetrated more than 40mm below the surface of tilled soil, which remained frozen until about 11am.

(2) Partly cloudy sky, low wind speed.

The maximum cooling rate was about 1.5˚C/h for a few hours after sunset, the minimum 0.3˚C/h for the hours before sunrise. Screen temperature fell only ten degrees to -0.5˚C and the temperature inversion was about one degree. Haze was sometimes visible before sunrise indicating that the air temperature had gone below the dew point.

(3) Substantial cloud cover.

Cloud cover was not complete but the average net radiation outwards was only 20% of that on clear nights. The screen temperature fell only five degrees from an afternoon maximum of 9˚C to 4˚C just before sunrise. Maximum cooling rate was 0.4˚C/h and minimum 0.2˚C/h. Little or no temperature inversion was measured.

(4) Changing cloud cover.

When a clear sky abruptly clouded over before 11pm the net radiation outwards dropped to a third of its previous level, rapid cooling (3˚C/h) stopped, surface temperature remained constant and screen temperature rose by one degree over the next two hours. On the nights when clouds rolled away after midnight both air and surface temperature fell about 3˚C over the next three hours.

The observations also show that the cooling near the surface on partly cloudy nights is typically only 3˚C less than that on clear nights. A night beginning clear and ending cloudy cools less than one starting cloudy and ending clear; the difference in overnight temperature drop is about 2˚C. After three or more hours clear sky at some time during the night there is 2˚C more cooling of the air near the ground than when it has been cloudy since sunset.

(5) North-westerly winds.

These strong Foehn winds kept overnight temperatures well above freezing. Little or no temperature inversion existed. Even so, screen temperature fell at 1˚C/h after sunset, the total overnight fall being more than 8˚C.

Effects observed on less than six occasions were:

(6) Rain.

Surface temperature was raised more than 2˚C above the expected no-rain value when measurable falls of rain occurred over short periods.

(7) Snow.

A snowstorm brought screen temperature to -4˚C one night and the coldest September temperature recorded in a ten-year period. It was a reminder that the coldest temperature may be produced by a 'freeze' or advection frost rather than a clear-sky radiation frost. The overhead sprinkler system in the orchard was turned on for two hours to protect the crop.

EFFECT OF WIND

Eddy conductivity is the main mechanism for heat transfer through the air near the ground. Parcels of air move vertically under the influence of wind, carrying heat with them. The amount of heat transferred, and the vertical temperature gradients depend on the strength of the turbulence generated by the wind. Eddy conductivity determines the temperature profile in the air of the 'boundary layer' 0.5 to 500m above the surface, infrared radiation having a much smaller effect than turbulence in this region.

During daytime the Earth's surface is heated by the incoming short-wave solar radiation. Up to 500 W/m^2 is transferred to the air in contact with the surface, heating and expanding it so that it rises due to buoyancy. As it rises it mixes with the cooler air above and a super-adiabatic temperature profile may be established (lapse condition). The amount of superheating will be less the higher the wind speed.

At night the surface cools by long-wave infrared radiation, and heat is conducted down through the air and into the surface .The rate of heat transport downwards by eddy conductivity at night may be less than a twentieth of that with which it may be transported upwards during daytime convection. A maximum of perhaps 25W/m^2 is transferred downwards at night through the lowest few metres of atmosphere. The air temperature profile at night depends largely on the horizontal wind speed. Well above the surface, where the wind speed is high, vertical eddies will be large, hot and cold air will mix readily, and only a weak temperature inversion will develop. The wind flow may become laminar as the surface is approached; the wind speed falls towards zero, vertical eddies become smaller, and the temperature inversion increases. Ten metres above ground the temperature inversion

may be as little as 0.05°C/m. In the first metre above the surface the air may warm by two degrees per metre.

An interesting phenomenon may sometimes occur on a clear frosty night. Air temperature and wind speed in the stable temperature inversion between the ground and 20m will increase smoothly with height and will be changing little with time. Quite suddenly the temperature 20m above ground begins to fluctuate and the wind speed and direction become erratic and variable. The average temperature at 20m falls a degree or so. These effects are the result of the onset of turbulence in what was formerly laminar airflow with small eddies. The average temperature inversion in the air between 1 and 20m is reduced because the large eddies of the turbulence permit a higher rate of heat flow than existed with the small eddies in the laminar flow.

A striking illustration of the effect of very calm conditions on air temperature was observed at a level site in South Africa (Surridge 1986) (Surridge & Goldreich 1988). The air at ground level at 6am can typically be 10 to 15°C colder than that at 100m and the inversion may not go above 100 metres. The wind speed at 100m was about 2m/s during these extreme inversions.

Air temperature was measured over a flat site at Leafield, UK between 1926 and 1930 (Johnson and Heywood 1938). The temperature inversion between 1.2m and 87.7m just before sunrise on mornings when there was no wind, following a clear still night, was typically 4°C. On one occasion an extreme temperature inversion, similar to those reported from South Africa, was observed. The air temperature difference between 1.2m and 12m was 5.6°C.

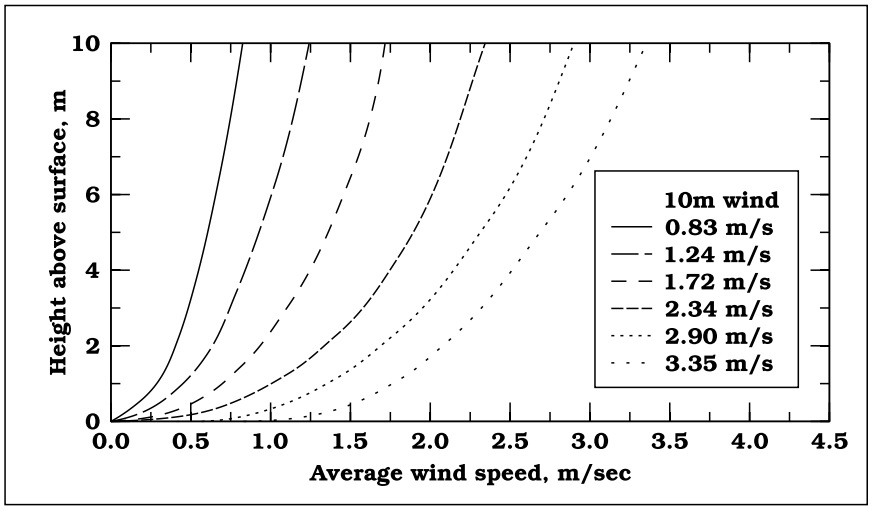

FIGURE 5.7. Typical wind speed profiles observed over flat land during radiation frosts at Lincoln. (After Young).

Measurements made at Lincoln in 1969-70 give a clear picture of wind speed from the surface to 10m during radiation frosts on flat land (Young 1971). Typical wind speed profiles derived from these data are shown in Figure 5.7. The wind speed profiles are almost identical to those obtained below 16m at Hay, Australia under similar conditions (Hicks 1976).

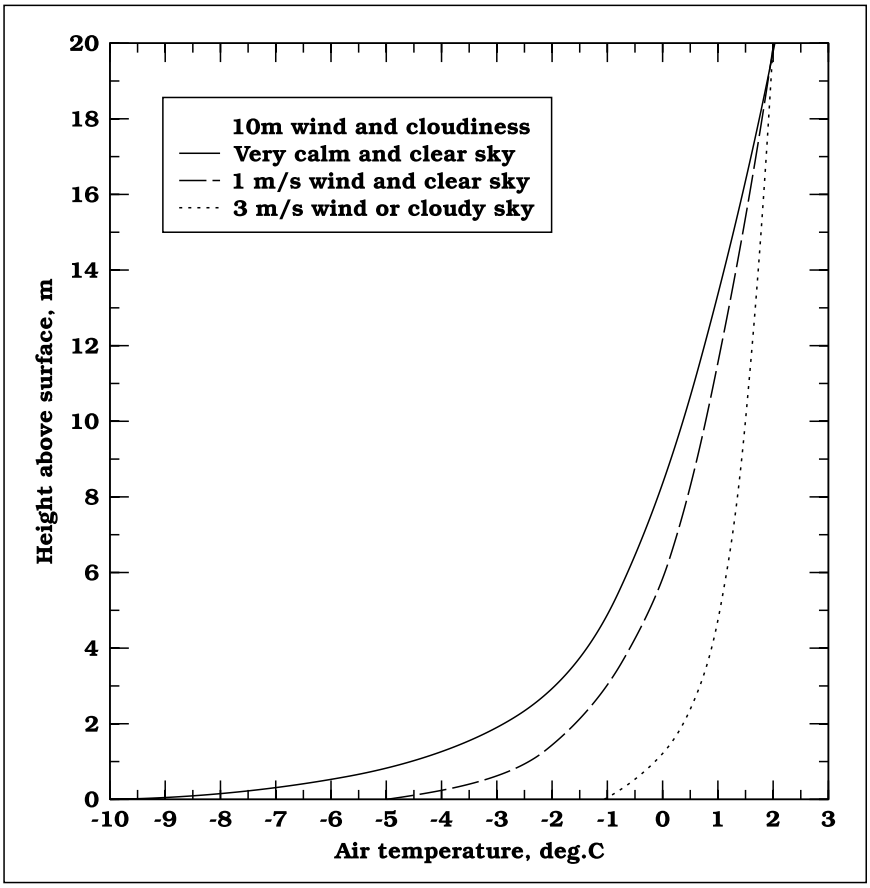

FIGURE 5.8. Typical air temperature profiles observed over flat land during radiation frosts at mid latitude, and their dependence on wind speed and cloudiness.

Figure 5.8 shows representative air temperature profiles below 20m, just before sunrise in a typical radiation frost on level ground. It is based largely on Young's 1971 and Hicks' 1976 data, and is extended to cloudy and very calm conditions from other published data. It assumes exponential wind and temperature profiles, and that the pre-sunrise air temperature at 20m is 2˚C. The curves may be raised or lowered accordingly if the 20m-air temperature differs from 2˚C and should still give a good representation of the effect of wind on the atmospheric temperature profile just before sunrise. Figure 5.8 shows that the air very close to the surface is one to five degrees cooler than the air at screen height. The air 10 to 20m above ground may be a suitable source of heat for frost fighting with a wind machine; it will be up to 6˚C warmer than the air at 1.3m.

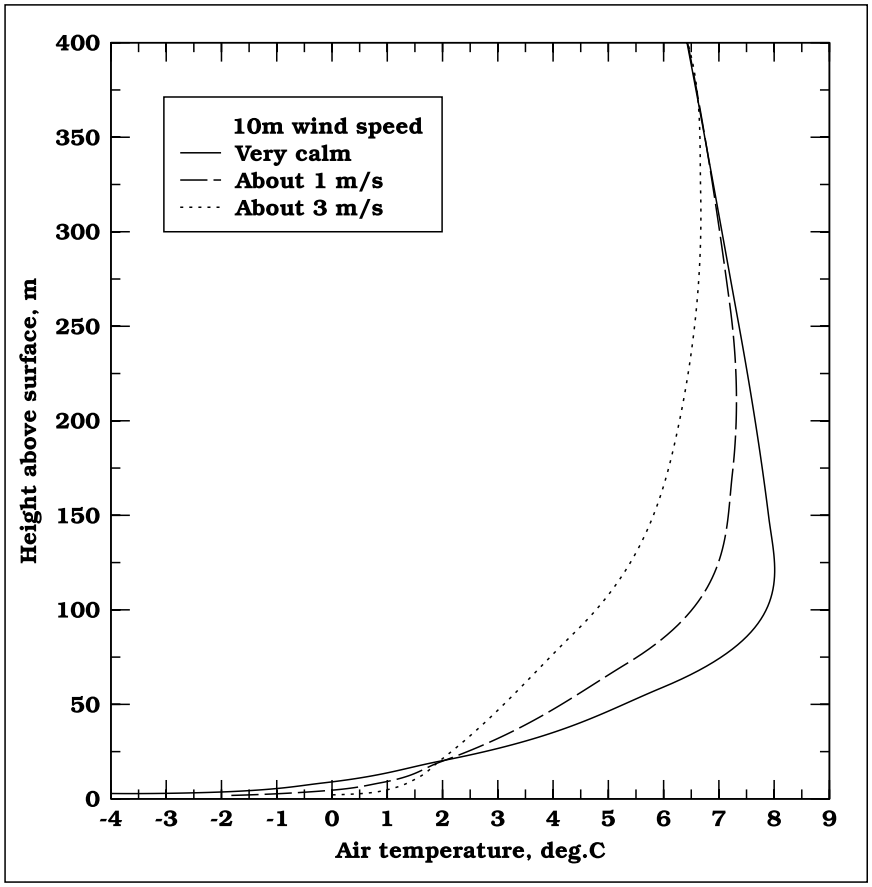

FIGURE 5.9. Typical air temperature profiles over flat land during radiation frosts with clear skies at mid latitude, and their dependence on wind speed.

The effect of wind on overnight cooling is shown in Figure 5.9. This set of curves is consistent with many of the published air temperature profiles for heights from the surface to 400m, for clear-sky radiation frosts over flat land at mid latitude, at the coldest time just before sunrise. Air temperature generally falls about 0.5˚C/100m at sunset, when the air 20m above ground is near 11.5˚C and the air 400m above ground is about 2˚C cooler. The air temperature at 400m falls about three degrees further from sunset to sunrise the next morning. Just before sunrise the air temperature at 20m appears to be about 2.5˚C, of the order of four degrees below that 400m above ground, irrespective of the wind speed and the total quantity of heat lost from the boundary layer overnight. The air temperature 20m above ground just before sunrise will then be of the order of nine degrees cooler than it was at sunset. The air at screen height will be about two to six degrees lower than that at 20m, depending on the wind speed, as shown in Figure 5.9. This suggests the possibility of frost prediction based on measurement of air temperature 20m above ground and wind speed during the night.

Low wind speed results in a cold surface, a severe frost, and strong temperature inversion because downwards-convective heat flow through the air is restricted. The proportion of heat supplied by the soil is increased yet the total heat lost by radiation is reduced because the surface is cooler and the sky appears to be warmer.

High wind speed increases the mixing of the air and increases the amount of heat that is carried downwards to the surface. This increases the cooling of the air, reduces the inversion strength, makes the sky cooler, and keeps the surface warmer than happens with low wind speed. A warmer surface radiates more heat towards the sky, and a cooler sky radiates less heat back to the surface. Proportionately less heat is taken from the soil. We have the apparent anomaly that more heat is radiated away from the surface on a windy night than when the air is still yet the ground and the air near the surface stay warmer, and the frost is less severe.

EFFECT OF CLOUD

Clouds scatter infrared radiation back towards the ground so the surface and air above it cool less on a cloudy night than when the sky is clear. The temperature inversion near the surface will be weak when the night sky is clouded; the inversion may even be absent and lapse conditions prevail. A complete overcast can reduce the loss of heat to the order of 10% of that possible under a clear sky and frost will be unlikely.

The observations made at Roxburgh, New Zealand (Ireland 1984) show that if the sky clouds over on a clear night the surface temperature may rise during the next hour or so. When the sky is not clouded over all night the air and surface temperature may eventually fall to much the same level as if there were no clouds. The following generalisations may be made about cloudy nights: A night beginning clear and then clouding over for several hours may eventually give temperatures similar to those for a night that has been cloudy since sunset. A few hours clear sky at any time of night may produce much the same low temperatures by sunrise as a clear sky all night since sunset. The minimum temperature reached may be more a function of wind speed than of cloudiness.

EFFECT OF FOG AND HAZE

Back radiation from fog reduces the radiant heat loss from the surface so damaging radiation frosts do not occur on foggy nights. Radiation fog or haze may develop close to the surface overnight when the air is cooled below dew point temperature. When saturation occurs above about 3˚C the fog will be composed of minute water droplets that are able to remain suspended in the air for a considerable time, and dew will form on upwards-facing surfaces. With dew point between 0 and say 3˚C the fog will be composed of water but the dew may freeze as non-crystalline rime. When the dew point is below 0˚C the fog will be formed of ice crystals and hoar frost forms.

If the fog layer grows sufficiently thick its upper surface becomes the effective infrared radiation surface. The upper surface of the fog may then cool further than the ground surface would have cooled in the absence of the fog, because the upper surface of the fog is not in close contact with the ground and the fog cannot extract heat by conduction from the soil. Minimum air temperature will be found near the top of the fog; below the fog the air and ground surface may warm up and stay above freezing.

EFFECT OF DEW

Water vapour reduces radiation loss so nocturnal cooling is generally less when the humidity is high. High humidity decreases the cooling rate in radiation frosts but a major benefit is the early appearance of dew; plant super cooling may be avoided (except in a few special cases). Settling of dew when humidity is high will ensure ice nucleation at the highest possible temperature, and may produce a hoar frost that is generally less damaging than a black frost.

Dew begins to appear on upwards-facing surfaces when they cool below dew point temperature. This usually occurs on clear nights, when the surfaces may be as much as 3˚C cooler than the surrounding air, and relative humidity exceeds 80 percent. Dew is a combination of water condensed from the air and water distilled after evaporating from plant surfaces (guttation) in the immediate vicinity of the dew-covered surfaces. The distilled portion may typically exceed the amount condensed from the air (Garratt & Segal 1988). Maximum dewfall is about 0.06mm/h and if 0.015 to 0.03mm/h condenses from the air it will release latent heat amounting to about 10 to 20W/m^2 to the surfaces it condenses on. This is of the order of a quarter to a half of the net radiation from the surface in a radiation frost after midnight, so the latent heat released by the dewfall must slow the cooling of the surface, bring it nearer to the temperature of the surrounding air, and provide significant frost protection when the dew point is near or above the critical temperature of the crop. (The dew distilled from plant surfaces does not contribute any net heat flux.)

EFFECT OF SOIL

Frost risk is greater over peat soils than mineral soils because heat cannot pass as easily through peat as through mineral soils. This gives the inland basin peat areas of Ireland a distinctive climate with minimum air temperatures slightly lower, air frosts more frequent in spring, ground frosts more frequent in summer, and soil temperatures lower in summer than on mineral soils. Temperature differences are generally less than 1˚C and growing conditions for frost-susceptible crops are less favourable on peat soils (McEntee 1977).

EFFECT OF ASPECT

The effect of aspect on naturally occurring plants is summed up in the quotation, ‘Banks that slope to the Southern Sky, Where languid violets love to lie’ (Sarah Helen Whitman). Plants growing naturally near their cold limit are found on slopes facing the Sun; those near their hot limit prefer slopes facing pole wards. In the Northern Hemisphere, southeastern slopes are warmer than southwestern slopes in summer, and southwestern slopes are warmer in winter, as a consequence of the cooling effect of the evaporation of overnight dew and frost on the slopes. Land that slopes down towards North in the Southern Hemisphere will generally be less frosty than south-facing slopes. Land lying to the Sun receives a greater amount of heat than flat land or land sloping away. South-facing slopes can lose the Sun for weeks in winter and may or may not make good orchard sites, depending on the winter chilling requirements of the crop.

EFFECT OF ELEVATION

The Earth’s surface and the air close to it generally become cooler as the ground elevation rises above sea level. Long term averages of monthly minimum screen temperature for

31 climate stations in Victoria, Australia show that minimum temperature falls about 0.4˚C/100m (0.004˚C/m) in summer and 0.3˚C/100m in winter (Kalma et al 1983). The same data reveal that sites could be found where the frost temperature could be up to two degrees higher or lower than would be expected solely on the basis of surface elevation. Depressions and stream channels are colder than average, crests and ridges are warmer. For sites at the same level a ridge may be up to 4˚C warmer than a hollow. A crop in a low-lying part of an area can be severely damaged by a frost while one on higher ground is largely unaffected. Radiation frosts will be generally consistent over large level areas with uniform vegetative cover but hollows or 'frost pockets' may fill with cold air that flows down from higher ground. A hollow in a generally level orchard can fill with a pond of cold air on a frosty night. Ponding of cold air is a hazard to crops such as grapes that are grown on fences or trellises where the support wires are a fixed height above ground, rather than maintaining a constant level relative to the general surface. The crop within a hollow only a metre deep may easily be two degrees cooler than that on the surrounding level ground. The effect of the cold air in a frost hollow less than a metre deep is shown clearly in the foreground of the photograph, Plate 5.1, of juvenile grape vines damaged by a late spring frost in November 1996 at Hastings, New Zealand. The vines on the level ground beyond the hollow were virtually undamaged.

EFFECT OF ELEVATION IN VALLEYS

Airflow in valleys during radiation frosts results from differences in buoyancy of adjacent parcels of air. The least buoyant air is that which has been cooled most by sensible and latent heat flows to the surface (which loses heat by infrared radiation towards the sky). On level open country or wide level valley floors a normal temperature inversion develops in a radiation frost, but there will be little tendency for a near-surface wind to develop. On surfaces with slopes of as little as one degree however, the difference in buoyancy of the air in contact with the surface and the slightly warmer air at the same level that is further away from the surface is sufficient to overcome the very strong stabilising effect of the temperature inversion and down slope flow results. The warmer air from the centre of the valley flows towards the valley sides to replace the cooler air near the surface that settles to lower levels. This can raise the surface temperature instead of allowing it to fall as would be expected on the basis of elevation above sea level. The temperature on the valley sides may then be controlled by the height of the surface relative to the valley floor. The existence of a warm belt along the sides of valleys has been known for centuries and the earliest villages, monasteries and country houses of Germany were built there. Plant growth zones that show the effect of temperature are seen. Figure 5.10 shows the close relation between night temperature and plant growth in the Bavarian Forest in 1931-32 (Geiger 1980). Beech shoots and leaves and blueberry shoots begin to grow three to eight days earlier about 100m above the valley floor than they do at the lowest and highest levels. The thermal belt usually found about 100m above the bottom of Appalachian valleys in USA is not generally affected by frost. The warm belt found on hillsides 100 to 200m above valley floors corresponds with the height of maximum temperature of the air in the centre of the valley during frosts.

The warmth of the air on the valley walls relative to that on the valley floor is related to the size and depth of the valley. In narrow deep valleys the frost temperature on the hillsides may be only a degree warmer than on the valley floor. In wide shallow valleys the frost temperature gradient on the hillsides may be of the order of 0.04˚C/m of elevation of the ground. The warm belt 150m above the valley floor in a frost may then be about 6˚C warmer

than the valley floor. Above the warm belt the air and surface on a frosty night will become colder as height increases.

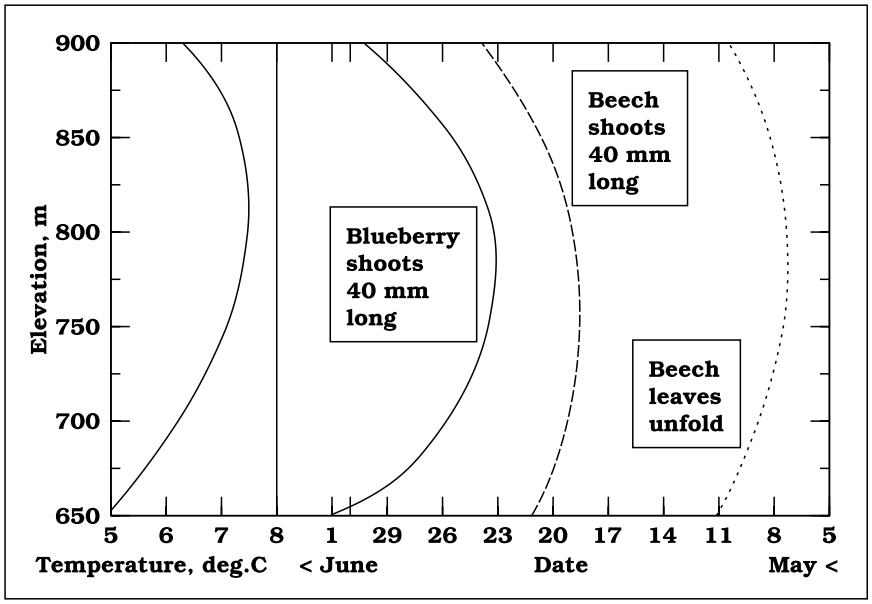

FIGURE 5.10. Average minimum night temperature near the ground and plant growth in spring, versus elevation on the Grosse Arber, for a period of 68 nights in May and June 1931 and 1932, showing the close relation between the warm belt and the commencement of new growth of blueberry and beech. (After Geiger).

The warm belt was observed when temperature was measured 1.3m above ground from a roving vehicle on frosty nights in the small basin of the Clutha River Valley at Roxburgh, New Zealand in spring 1981. At this point the valley floor is about 3km wide and the surrounding hills about 500m high. Maximum temperature occurred on the hillsides about 120m above the river. It was only 1 to 3˚C warmer than on the valley floor (Ireland 1984).

Frosts were studied in the Nittany Valley; a broad valley bordered by narrow ridges, characteristic of the agricultural region of the Appalachian Mountains of Pennsylvania, USA (Hocevar and Martsolf 1971). Air temperature was measured from a roving vehicle in the hour before sunrise. Most of the variation in temperature could be explained by the elevation relative to the bottom of the basin. The typical upslope increase of 0.062˚C/m was suggested as a good basis for predicting the relative frost danger of similar valleys from their contour maps.

EFFECT OF KATABATIC WIND

The cold air on frosty nights tends to flow down the centre of a valley forcing warmer air to rise and return to the valley walls higher up. It can have a much more pronounced effect than making hollows colder than ridges. In narrow valleys surrounded by large areas of high land the valleys can be filled overnight with cold air that has flowed down from the hills. Down slope winds can be strong as well as being very cold and can cause severe frost

damage. These winds are called katabatic flows and the frost results from advection rather than being solely due to radiation. (An advection frost resulting from katabatic flow should not be confused with an 'Advection Freeze' caused by an influx of sub-zero air over a large area as a result of the passage of a large scale weather feature.)

Down slope winds at night on the slopes of the north chain of mountains at Innsbruck, Austria and the winter morning wind down the Davos Valley in Switzerland had maximum speed of 2.5m/s about 20 to 40m above the ground (Geiger 1980).

Downhill katabatic flow was found to be confined to a layer about 40m thick centred less than 40m above ground in a study made on two nights in the Latrobe Valley, Australia in spring 1975 (Manins & Sawford 1979). The maximum wind speed in the katabatic flow was about 3.4m/s. The air in the first few metres above the ground was apparently flowing in a 'skin' independent of the katabatic flow above. Wind direction in the surface skin flow was variable and the wind speed was typically of the order of 0.5 to 1.5m/s.

Smoke often shows the effect of katabatic flow. Plate 5.2 shows the situation often seen in the katabatic flow down the Hutt River Valley near the head of the Wellington Harbour at Lower Hutt, New Zealand. Smoke from chimneys in the centre of the valley is carried almost horizontally (from right to left in the photograph) down valley by a brisk wind. Near the valley walls smoke often goes straight up and the top of a plume may be blown slowly up the valley by a rather irregular wind.

EFFECT OF LAKES, HARBOURS AND RIVERS

Large tracts of water have a warming effect on overnight minimum temperatures. Sites close to the sea or a large lake may rarely experience a screen frost when areas a few kilometres inland can regularly record fifty screen frosts a year. The 'Grape Belt' is a belt of land running some sixty miles along the southern shore of Lake Erie, USA, that has long and mild autumns, and less severe winters than more inland regions at similar latitude.

The Wellington Harbour in New Zealand is approximately circular with a diameter of about 8km. It is surrounded by steep-sided hills some 200m high. At the northern end of the harbour the Hutt River Valley narrows from 5km at the water's edge to less than 1km twelve kilometres up the valley. Air frost may occur once a year at the harbour and thirty to forty times a year at Wallaceville only 17km up river from the harbour. Notwithstanding the significant down river flow of cold air on frosty nights shown in Plate 5.2, the minimum recorded screen temperature near the harbour is 5°C warmer than at Kaitoke, at the head of the valley, 30km away. The minimum temperature at the harbour would be about 2°C warmer due to its lower elevation (223m below Kaitoke), leaving up to 3°C to be accounted for by the warming effect of the harbour and the river, and the difference in buoyancy needed to sustain the katabatic flow down the valley. Mirages are common on Wellington Harbour on frosty mornings. They are produced when the cool katabatic wind flows across the expanse of warmer water. Plate 5.3 shows such a mirage seen from a height of 3m above the water. The small island was 6km from the camera and the white ship about 8km. A small runabout is seen just in front of the ship and closer to the camera than the apparent horizon. The true horizon between the ship and the runabout is invisible. The water temperature was about 8°C and the air in the katabatic flow a few degrees above zero.

The warming of the air close to a large river is illustrated by minimum overnight screen temperature at Roxburgh, New Zealand in spring 1980. It was 1 to 2°C warmer near the Clutha River than it was at least 200m away. The river water when these measurements were made was about 8°C and the air away from the river was typically between 0 and 4°C (Ireland 1984).

EFFECT OF CITIES

The climate of towns and cities is warmer than that of the surrounding rural areas because buildings and roads absorb and retain more heat from sunlight than do vegetative surfaces. Artificial (man-made) heat is often released from buildings and from activities nearby, adding to the natural warming. It has been suggested that much of the apparent global warming could be accounted for by the gradual change in the surroundings of the long-term climate stations that were situated close to major cities. One estimate was that nearly 0.17°C of the apparent warming over the 34 years before 1988 was due to artificial warming of the primary station network, and was at least as large as any of the observed trends (Reifsnyder 1989). Later estimates of global warming have made allowance for this effect.

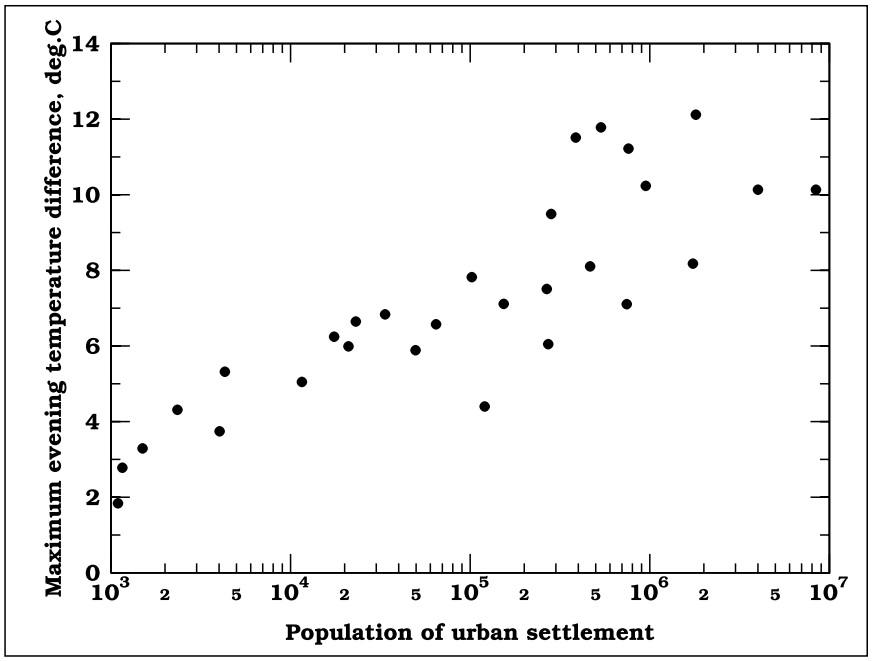

FIGURE 5.11. The maximum difference between air temperature measured in towns and cities, and in nearby rural areas, showing that the urban areas are warmer than the surrounding countryside. The maximum 'heat island' effect usually occurs at night. (After Oke).

During daytime in midwinter the artificial heat released from London, UK averages more than 100W/m^2 over an area of about 20km^2 and overnight more than 20W/m^2 over at least 200km^2 (Harrison et al 1984). On one occasion during fine summer weather in June 1959 the maximum temperature in the inner city was about 4°C warmer than in the surrounding country. The following night the minimum temperature was about 5°C warmer in the city (Lamb 1972).

The atmospheric temperature and humidity profiles above a small city (population about 300,000) with manmade heat of the order of 4W/m^2 have been compared with those over flat countryside about 30km away (Tapper 1990). The air temperature and humidity about midnight on clear sky nights were measured to a height of 500m over Christchurch, New

Zealand and at Lincoln. The mean urban temperature inversion was 0.06.7˚C/m compared with 0.09.3˚C/m for the rural site between the surface and 100m or the surface and the top of any surface-based inversion. Minimum temperature in the city was about 2.3˚C higher than in the country. The humidity in the city about midnight also exceeded that in the country, typically by about 0.8g/kg near the surface rising to some 1.5g/kg more 100m above ground. The dew point in the city would therefore be about 2˚C higher than in the country.

The difference between city and rural air temperature is usually most pronounced in the evening. The maximum temperature difference for 29 settlements ranging from 1,000 to 8,500,000 inhabitants is shown in Figure 5.11 (Oke 1973). It is roughly proportional to the logarithm of the population. Settlements of only 1,000 people can be up to 2˚C warmer than the surrounding countryside and the maximum difference reaches 10˚C for cities with more than 500,000 inhabitants.

CHAPTER SIX

FROST PREDICTION AND PROTECTION MODELS

INTRODUCTION

It should be possible to predict the occurrence and severity of a simple radiation frost, and the time at which a dangerous temperature will be reached, by using a suitable model and by making relevant measurements about sunset, assuming that the sky remains clear and the wind speed is low. The measurements required for the simple empirical models based on Brunt's analysis are typically screen or dry bulb temperature, wet bulb temperature or relative humidity before sunset and net radiation after sunset. Accurate prediction according to Newton's 'law of cooling' can be made some time after sunset from measurements of temperature with a single thermometer.

Modelling the heat flows at the ground surface, and at upper and lower crop surfaces in a radiation frost, shows the factors that may be modified by a frost protection strategy, in order to hold the crop at a safe temperature. The worked examples describing the partitioning of the heat flows to and from crops are introduced to show how the various methods used for frost protection may be expected to work and their limitations. In later chapters the models are used to interpret the results achieved by the various methods used to reduce frost risk or prevent damage to crops.

FROST PREDICTION – BRUNT MODEL

The first approximation for nocturnal cooling to be generally accepted was proposed in 1941 (Brunt 1952). The ground surface temperature is predicted to fall in proportion to the maximum net radiation from the surface to the sky shortly after sunset and the square root of time since sunset or a change from overcast to clear sky. The analysis assumes that the net radiation from the surface is zero and then instantaneously jumps to the value Qrn, the maximum radiation reached shortly after sunset.

Brunt postulated that net radiation would be sensibly constant all night. This requires the sky temperature to fall in unison with surface temperature. This assumption fails to take account of the fact that the sky temperature, which is lower than the surface temperature, depends on the changing temperature profile in the lowest few hundred metres of the atmosphere at night and falls less than the surface temperature as the night proceeds. So the net radiation reduces exponentially when the atmospheric temperature inversion increases, reducing the cooling rate as time passes.

The conductivity of the air ka was originally assumed to be that for still air at the surface, making the atmospheric effect negligible. Later estimates took account of the fact that heat is carried downward through the air to the ground at night by eddies that cause mixing as well as by conduction through the air. When a wind is blowing, as is always the case in nature, the air conductivity is increased several orders of magnitude by the turbulent eddies. The temperature profile that develops in a nocturnal temperature inversion is the result of the change of wind speed and the resulting eddy conductivity with height. Near the surface wind speed is low, eddies are small, eddy conductivity is low, and temperature gradients are large. Higher up wind speed increases, eddies are larger, eddy conductivity is

higher, and temperature gradients are smaller. Substituting for the still-air value the value for ka appropriate to eddy conductivity, heat transferred from air to surface assumes a significant proportion of that radiated, reducing the predicted overnight cooling accordingly.

Measurements of eddy conductivity very near the surface are difficult and few results are available. The heat flux from air to surface may be estimated by measuring the flux say 10m above ground and assuming that it is about 80% of the flux from air to surface. Downwards flux near the surface at night has been found to range between 5 and 35W/m^2 (Estournel et al 1986).

Allowing for the heat flow from air to surface, the Brunt formula for Tg, the temperature of the surface after sunset relies on measurement or estimation of several variable quantities. It is (Groen 1947)

$$Tg = Tg(sunset) - \frac{2*Qrn*\sqrt{t}}{\sqrt{3.14}*(ps*cs*\sqrt{ks}+pa*cp*\sqrt{ka})}$$

where Tg(sunset) = sunset or pre-change surface temperature (˚C)
Qrn = maximum net radiation after sunset at the surface (W/m^2)
t = time since sunset or since the change of net radiation from zero to the value Qrn (hours)
ps = soil density
cs = soil specific heat
ks = soil specific conductivity
pa = air density
cp = air specific heat
and ka = air specific conductivity

Soil conditions are reasonably stable in the absence of rain or irrigation so variability of the prediction from day to day is more likely to be due to changes in the atmospheric conditions, especially humidity, wind speed and cloudiness. The Brunt formula for forecasting ground surface temperature on a cloudless night can then be simplified and used to forecast screen temperature Ts, by substituting an experimentally-determined constant K for the atmospheric variables, pa, cp, ka, and the site-specific ground variables ps, cs, ks. The prediction can be modified by a factor based on the dew point, when the cooling will be proportional to (1-0.025*Tdp), a factor (1+0.015*Ta) for the effect of the average overnight temperature Ta, and a factor (1-kc*C) for the effect of clouds. There does not appear to be any estimate available for the effect of wind. Then, for a forecast based on measurements made before sunset

$$Ts = Ts(sunset)-K*\sqrt{t}\ (˚C)$$
$$= Ts(sunset)-Ko*(1-0.025*Tdp)*(1+0.015*Ta)*(1-kc*C)*\sqrt{t}$$

where Ts(sunset) = screen temperature at sunset (˚C)
K = Ko*(1-0.025*Tdp)*(1+0.015*Ta)*(1-kc*C)
Ko = a constant that is site specific
Ta = Ts(sunset)-K/2
e = vapour pressure (hectopascals)
and t = time since sunset (hours)

K is of course approximately equal to the excess of the sunset temperature over the temperature about sunrise. It has been established for two stations in the USA; K = 12.32 for El Centro, California and 16.1 for Phoenix, Arizona (Kangieser 1959).

The Brunt model and its derivatives can predict the minimum temperature that is reached about sunrise quite well if an appropriate value of K is used at sunset or if the maximum value of Qrn is measured shortly after sunset, but they predict temperatures that are too low just after sunset and too high later in the night because the square root is not the correct factor to use for time.

NET RADIATION – CLEAR SKY

Radiation frost results from the loss of long wave infrared (heat) radiation from the surface of the ground towards the sky. The heat lost from the ground surface at night depends on the 'net radiation', the excess of the heat that is radiated upward from the surface toward the sky over that radiated downward from the atmosphere toward the surface. Frost prediction formulas and cloud detection are often based on measurements of net radiation. All bodies emit radiation in proportion to the blackness and the fourth power of the absolute temperature (Kelvin) of their surfaces. The outward flux Q from the surface of a body is usually taken by convention to be a positive quantity and given by the general formula

$$Q = S*E*T^4 \ (W/m^2)$$

where S = Stefan-Boltzmann Constant (5.67*10-8)
E = emissivity (= 1.0 for a 'black' body)
T = surface temperature (Kelvin)

With this convention the net radiation in sunshine during the day will be a negative quantity reaching a maximum about noon less than $800W/m^2$ and the maximum at night a positive quantity reaching perhaps $100W/m^2$. The net radiation Qrn at the ground surface in the absence of sunshine is usually taken by convention to be the difference between Qru the upward and Qrd the downward long wave infrared fluxes at the surface

$$Qrn = Qru-Qrd \ (W/m^2)$$

The upward radiation from the surface of the ground Qru toward the sky depends on the temperature of the surface. The downward radiation from the atmosphere Qrd into the ground can be thought of as coming from a surface whose temperature is the temperature of the sky.

It is sometimes assumed that the ground surface emits infrared radiation as if it were a perfectly 'black' body for which the emissivity Eg can be taken as unity. Infrared emissivity of bare soil is 0.90 to 0.95, of water 0.995, and of leaves from 0.94 to 0.995 (Monteith & Unsworth 1990), so assuming an emissivity of 1.0 in preference to 0.95 may overestimate the heat radiated from the surface by up to $15W/m^2$.

'Sky temperature' may be defined as an equivalent radiative temperature Tsky for a sky with an emissivity equal to that of a black body (Esky = 1.0). In the absence of the atmosphere the sky temperature would be the radiation temperature of space, about 2.7 degrees above absolute zero (i.e. 2.7K or -270.45°C). The greenhouse gases water vapour, ozone, carbon dioxide, nitrous oxide, and methane absorb and re-radiate infrared radiation, and the sky temperature, looking up from the Earth's surface, is of the order of 15°C below screen temperature.

The concept of sky temperature assumes that radiation coming down through the atmosphere has a wavelength spectrum and emissivity the same as that of a black body whereas with clear skies there is a radiation deficit for wavelengths between 8 and 14um, the 'atmospheric window', and the emissivity is less than unity. The radiation that is lost through this 'window'

is particularly sensitive to the amount of water vapour in the atmosphere, being greatest when the absolute humidity is lowest. The other 'greenhouse gases', carbon dioxide, methane, nitrous oxide and ozone contribute little to the 'greenhouse effect', because their concentrations are very small (they are often called 'trace gases'), and they change little in comparison with water vapour, whose concentration may vary greatly from day to day. In calculating net radiation the sky temperature and black body emissivity are usually replaced by the temperature of the air near the ground and an 'effective sky emissivity'.

Several determinations of effective sky emissivity Es have been derived from measurements of atmospheric humidity. They assume that only the changes in water vapour are large enough to significantly affect clear sky emissivity from day to day. A large number of radiometer, air temperature and humidity observations under clear skies have been compared to deduce effective sky emissivity (Berdahl & Fromberg 1982). It was found that a reasonable approximation for average night time effective sky emissivity Es could be expressed as a linear function of dew point temperature measured somewhere near the ground

$$Es = 0.741+0.0062*Tdp$$

where Tdp = dew point near the surface (°C)

This gives the net radiation Qrn at the ground surface at night as

$$Qrn = Qru-Qrd\ (W/m^2)$$
$$= S*(Eg*Tg^4-Es*Ts^4)$$

where $Qru = S*(Eg*Tg^4)$ (i.e. from the surface toward the sky)
and $Qrd = S*(Es*Ts^4)$ (i.e. from the atmosphere toward the surface)
S = Stefan-Boltzmann Constant (5.67*10-8)
Eg = ground surface emissivity (about 0.95)
Es = effective sky emissivity (about 0.74)
Tg = ground surface temperature (Kelvin)
and Ts = screen temperature (Kelvin)

The heat lost from the surface by radiation is replaced by conduction upward from the soil and by radiation and convection downward from the air near the surface. The surface, the soil, and the air near the surface cool down. The surface typically cools about 3°C/h at sunset, losing net radiation at about 80W/m^2 to a clear sky. The air more than a few metres above the surface cools somewhat less than the air in contact with the surface, a temperature inversion develops, and the sky temperature falls more slowly than the surface temperature. The net radiation reduces quickly as the surface cools. Net radiation from the surface reduces by about 5W/m^2 for each degree that the surface cools relative to the sky. In the first three hours after sunset the surface will cool about 6°C more than the sky and net radiation will reduce from about 80W/m^2 to 50W/m^2. Net radiation then reduces little more before sunrise and surface cooling settles toward perhaps 0.3°C/h after midnight. If the dew point is reached the cooling rate may be reduced still further as the dew gives up latent heat. About sunrise net radiation reverses and the surface warms at 2°C/h or more for the next few hours.

NET RADIATION – CLOUDY SKY

Frost is rarely a problem on overcast nights because clouds are very effective 'blankets' that scatter infrared radiation back towards the ground and reduce net radiation to a low value.

The dependence of heat loss on cloudiness was measured in the Stolz Alpe in winter 1927 and compared with the model

Qrn(cloudy) = Qrn(clear)*(1-kc*C)
where C = cloudiness (0 to 1)
and kc = a constant depending on cloud type and elevation
= 0.76 for low thick clouds
= 0.52 for high thin clouds
= 0.26 for thin high veils

The comparison of the observations with the model suggested that cloudiness is related to the height of the clouds. Thin high clouds reduce net radiation only slightly, a complete overcast of low clouds reduces net radiation to 14% of that to a clear sky, a fog reduces it to about 7% (Geiger 1950), and the cooling rate will be reduced in the same ratio. Other observations show that surface temperature falls more slowly or rises on a frosty night when clouds appear or when fog develops, even though there is still a net radiation loss from the surface. This apparently anomalous behaviour can however be explained by noting that under a clear sky at night the surface cools more than the air above and the soil below, and that the heat that was flowing at a nearly constant rate, towards the cooler surface from the warmer air and soil before the clouds or fog appeared, will then flow at a gradually-reducing rate, and the surface temperature falls more slowly or rises until a new equilibrium is reached. A change from cooling when the sky is clear to warming in excess of one degree an hour can occur when the sky completely clouds over. Figure 4.1 shows how radiation fog can change air temperature from cooling at 0.6deg.C/h to heating at 2.2deg.C/h (Leuning & Cremer 1988).

EMPIRICAL FORMULAS FOR MINIMUM AIR TEMPERATURE

The difficulties with the Brunt derivatives for predicting overnight cooling based on measurements made before sunset have led meteorologists to empirical formulas that predict only the lowest screen temperature Ts(min) that will occur prior to sunrise. These formulas may have little justification other than that they work. They are based on an analysis of measurements of temperature over many nights and may include allowance for wind speed and cloudiness. Many of them have been outlined in a World Meteorological Organisation review (Bagdonas et al 1978).

The simplest formulas for screen minimum temperature use the idea of a daily temperature range that is subtracted from the measured maximum temperature to predict the overnight minimum, i.e.

Ts(min) = Ts(max)-Trange

Another basis for prediction is that the range will most likely be twice the measured drop in temperature from maximum to a ‘median hour’, giving

Ts(min) = Ts(max)-2*(Ts(max)-Ts(med))
= 2*Ts(med)-Ts(max)

Many formulas take account of atmospheric humidity (Sutton 1953). In France the lowest temperature reached by the air 100mm above the ground was based on the simplified Brunt formula

$T(min) = T-k*(a-b*\sqrt{e})$
where T is measured early at night
and k, a, and b are site specific.

Faust forecast ground frost if the sum of screen and half the dew point temperature at 2pm was less than 17deg.C (or a number near 17 depending on location) (Searle 1973)

$$17 > Ts(2pm)+0.5*Tdp(2pm).$$

Kammerman assumed that the minimum will be a constant number of degrees, a, below the wet bulb temperature at a certain time, say sunset. Then

$$Ts(min) = Twet(sunset)-a$$

Angstrom found better results with

$$Ts(min) = Twet(sunset)-a*Ts(sunset)-b$$
where a and b are constants

The 'wet bulb minimum temperature method' of Keyser subtracts the average difference between 5pm wet bulb readings and minimum temperatures from the 5pm reading, giving

$$Ts(min) = Twet(5pm)-(Twet(5pm)-Ts(min))av$$

Humphreys proposed an 'evening dew point method' that predicted a minimum temperature approximating the evening dew point. This gave

$$Ts(min) = Tdp(evening)$$

Several formulas use afternoon screen temperature as well as the wet bulb temperature or the dew point as input to minimum temperature prediction, as in

$$Ts(min) = Twet(afternoon)-a*Ts(afternoon)-b$$
or $Ts(min) = a*Ts(afternoon)+b*Tdp(afternoon)+c$
where a, b, and c are constants

Young has used relative humidity, dew point and cloudiness in preference to wet bulb temperature in a very successful but rather laborious formula

$$Ts(min) = Tdp(evening)-(H-n)/4+Vd+Vh$$
where H = relative humidity in the evening (0 to 100)
and n = 20, 30 or 40 for clear, partly-cloudy or cloudy skies
Vd and Vh are empirical parameters

Allen's simplification of Young's formula is

$$Ts(min) = 2/3*Tdp+(98-H)/12$$
where Tdp and H are measured at 4.45pm.

FROST PREDICTION – NEWTON'S LAW OF COOLING

Isaac Newton (1642 – 1727) discovered that the rate of change of temperature of a body that is not much warmer than its surroundings is the result of heat loss by a combination of conduction, convection and radiation, and at any time is approximately proportional to the temperature excess of the body over its surroundings. According to Newton the excess temperature Tt of the body over its surroundings at time t after the first reading is

$Tt = Ti * \varepsilon^{-a*t}$

Ti = the initial excess of temperature of the body
over its surroundings at the time t = 0
ε = 2.718281
t = time after first reading
a = a constant

It appears that Newton's law of cooling has not previously been applied to radiation frost prediction. Analysis of several published curves of temperature during nocturnal cooling shows that they are all classic cases of Newton's law of cooling (Data extracted from papers by Brooks et al 1962, Kuo 1968, Parton & Logan 1981, Heilman et al 1970, Ireland 1984, Wann et al 1985). Figure 6.1 shows a typical clear-sky cooling curve for air temperature according to Newton's law and a Brunt prediction of the overnight cooling for comparison.

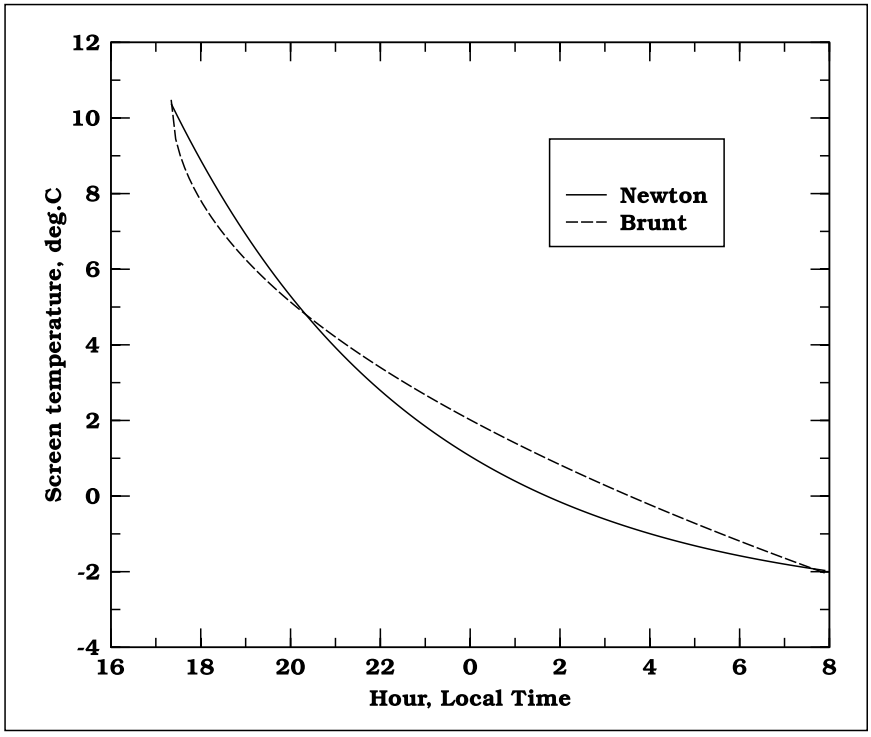

FIGURE 6.1. Temperature of the air overnight with a clear sky and little wind, assuming that it may be represented by Newton's law of cooling or by Brunt's approximation.

Using Newton's law the temperature of the air, the crop or the surface, for the remainder of the night can be forecast from a minimum of three readings of a suitable thermometer over a few hours beginning at or after sunset, assuming that conditions remain unchanged. The maximum predicted fall in temperature will be when the sky is clear, wind speed and dew point are low. This is the 'worst case' that can occur any night when conditions such as cloudiness or wind speed change and is the only 'fail safe' forecast for frost protection. If the measurements are made when the sky is not clear, or if there is a wind, the predicted temperature fall will be less than for the worst case and the forecast should not be relied on for more than about an hour because if the sky clears or the wind drops the temperature will fall towards the worst case. A new determination when the sky clears or the wind drops will give a new worst case forecast.

The prediction is made by using a computer to fit the measured temperatures to the formula for Newton's law of cooling. The temperature at any time following the last reading is then predicted using the coefficients determined by the computer with a suitable least squares fitting software routine. The temperature Tt to which the air, crop or surface falls is given by

$$Tt = To - K*(1-\varepsilon^{-a*t})$$

where To = temperature of air, crop or surface at first reading (˚C or ˚F)
ε = 2.718281
t = time after first reading (usually after sunset) (hours)
K = a constant that is site and weather specific
and a = a constant that is site and weather specific

The constants K and a are specific for a particular place and a particular night and are determined by the fitting procedure. As with predictions based on Brunt's analysis, K is approximately equal to the excess of the temperature at first reading over the temperature that will be reached about sunrise. Prediction beginning at sunset, before the minimum three readings are taken, is made by using values for K and a that have been found to be appropriate on previous occasions, allowing for the effect of dew point, average overnight temperature and cloudiness. Humidity has the greatest effect of the three factors determining the value of K. If K = 14˚C when the dew point is 0˚C then K will be 10.5˚C when the dew point is 10˚C and 17.5˚C when the dew point is -10˚C. If the average temperature overnight is 10˚C instead of 0˚C then K is increased from 14˚C to 16˚C. K would not normally be corrected for cloudiness or wind because the greatest frost danger is when the sky is clear, there is little wind and cooling is worst case.

The difference between Newton's formula and the simplified Brunt formulas is that the computer can work out the correct values for K and a to be used at any time during the night, based on the cooling that is actually occurring at the time; the Brunt methods use an assumed value for K at sunset or a measured value of Qrn after sunset and new guesses must be made manually. Large values of K predict low temperatures, large values of a predict rapid cooling. Limits may lie in the range $5 < K < 25$ and $0.1 < a < 1$.

In the absence of a computer the measured temperatures may be compared with a set of Newton's cooling curves such as those in the Appendix calculated from representative values of K and a, choosing to use the curve that gives the best fit as the prediction to use for the remainder of the night. The minimum temperature reached about sunrise is always just a little warmer than the sunset temperature minus K degrees, irrespective of the value of a, but the rate at which the temperature falls depends on the value of a. When the danger

temperature is likely to occur well before sunrise the right value of a has to be chosen. It will be better to assume a large value for a so as to predict a lower temperature than that which eventuates.

MODELLING GROUND SURFACE HEAT FLOW

The assumption of constant temperatures used in simple models of overnight heat flows ignores the fact that the air and ground are finite sources of heat, and the near-surface temperatures must fall as time passes. In a simple radiation frost the near-surface temperatures are not constant but fall quickly about sundown and more slowly as time passes, reaching minima about sunrise, provided the sky remains clear and there is little wind. Near-surface temperatures fall about 3°C/hour after sunset; after midnight they may fall about 0.3°C/h until sunrise.

Assuming that there is no net heat flow either into or out of the surface, and that the surface neither warms nor cools relative to the surroundings, the net radiation at the ground surface at night, to a first approximation, has to be balanced by the sensible and latent heat flows from the air and from the soil below the surface to the surface. The partitioning of the heat flow may be written as

$$Qrn = Qc+Qe+Qg \text{ (at equilibrium there is no net flow)}$$

where Qrn = net radiation, positive upward (W/m^2)

Qc = sensible heat flux, positive for air-to-surface flow (W/m^2)

Qe = latent heat flux, positive for dewfall (W/m^2)

and Qg = subsurface heat flux, positive upward (W/m^2)

With a clear sky at night, the sky is cooler than the surface, net radiation upward is a positive quantity that can be measured using a net radiometer; it is typically between 40 and 100 W/m^2. On a clear night the surface cools below air and subsurface temperatures, heat flows from the air and from below ground towards the surface, sensible heat from the air and subsurface heat are positive quantities. When the surface is colder than the dew point or frost point Qe is positive, latent heat is given up to the surface by condensation of atmospheric water vapour and dew or ice forms. The surface temperature is held closer to air temperature than it would be if the condensation had not taken place. Dew or frost continues to build up on the surface for as long as its temperature stays below the dew point or frost point. In the limit the surface temperature may be held at the dew point or frost point.

Sensible and latent heat transfer between air and surfaces in the open is between one and two times, and the average about 1.5 times that predicted from laminar flow theory. The increase is believed to be due to the turbulence of natural winds (Pearman et al 1972).

The sensible heat flux between air and surfaces in the open may be estimated with sufficient accuracy for this model by defining a convective heat transfer coefficient, hc, that is proportional to the square root of wind speed, and inversely proportional to the square root of a 'characteristic' dimension (Jones 1992). A general formula for the sensible heat flux Qc that is proportional to the temperature difference between the air and the surface is then

$Qc = hc*(Tair-Tsurface)$ (W/m^2)
where $hc = Cc*\sqrt{(u/d)}$ $(W/m^2/°C)$
Cc = a constant related to the characteristics of the surface
u = wind speed near the surface (m/s)
and d = a characteristic dimension related to the size of the surface, or the distance from it where u is measured (m)

Noting that the heat convected downward through the air near the surface at night has been found to range between 5 and 35W/m^2 (Estournel et al 1986), the sensible heat flux Qc from air to the ground surface that may be appropriate in a radiation frost may then be obtained by assuming Cc = 7.5 and modifying the general formula to

$Qc = hc*(Ts-Tg)$
$= Cc*\sqrt{(u/d)}*(Ts-Tg)$
where Cc = a constant related to the characteristics of the ground surface (assume Cc = 7.5)
Ts = screen temperature (°C)
Tg = ground surface temperature (°C)
u = wind speed 1.3m above ground (m/s)
and d = 1.3m

Alternatively, assuming Cc = 7.5, the sensible heat transfer coefficient hc, for wind speed in the range appropriate for radiation frost, may be obtained from Figure 6.2. This approximation may also be appropriate for sensible heat transfer from ground to air when the surface is made warmer than the air by water sprinkling for frost protection. The air temperature and wind speed are measured at screen height for this approximation.

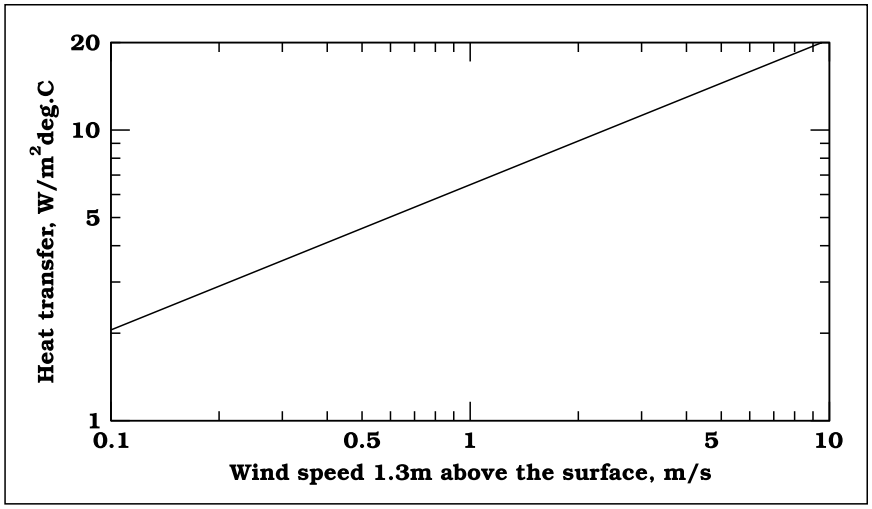

FIGURE 6.2. Sensible heat transfer between air and the ground surface during temperature inversion conditions at night, as a function of the difference between air temperature 1.3 metres above the surface and surface temperature, and wind speed 1.3 metres above the surface.

Several models have been proposed for latent heat transfer by evaporation from a wet surface (Penman 1948, Tanner & Pelton 1960). They are all based on the idea put forward by Dalton in 1802 that evaporation is proportional to the difference between the saturation vapour pressure at the surface temperature and the ambient vapour pressure in the surrounding air multiplied by a wind factor. The same models may be used for the reverse process, condensation in dew or frost.

When the surface is colder than the dew point or frost point Qe is positive, dew or frost builds up, when the surface is warmer than the dew point or frost point Qe is negative and water or ice on the surface evaporates. Maximum latent heat flux Qe between air and surface (positive for dewfall and negative for evaporation) may be calculated by the formula using the sensible heat transfer coefficient hc, surface and dew point temperatures Tg and Tdp, giving

$$Qe = 0.77*hc*(Tdp-Tg)$$

The subsurface heat flux Qg may be a mixture of conduction, water movement, evaporation and condensation, freezing and thawing, and even radiation should large enough air spaces exist in the soil. It may be estimated by measurement of temperature at different depths, by use of a flux plate, or by balancing the heat flux equation after estimating the other fluxes. It is typically about 35W/m^2 (i.e. upward from the soil to the surface) after midnight during a radiation frost and changes little until sunrise.

FROST ON PLANTS

A common misconception is that the temperature of a crop in a radiation frost is the same as the temperature of the surrounding air, and that it is the cold air that damages the crop. The real situation is that plant surfaces cool below the temperature of the surrounding air in a radiation frost at night, and the air actually keeps the crop warmer than it would otherwise be. Crop surfaces cool until the heat transferred to them from the air balances the heat lost by radiation. Most of the foliage is elevated above the ground, so the air is the only effective source of heat available. The temperature of foliage two metres above ground is controlled by radiation, air temperature and wind speed, and not closely related to ground or grass temperature.

The hoar frost on a leaf is predominantly formed at the leaf margins as seen in Plate 6.1. It may be expected to form first towards the centre because it is colder there than at the edges in a radiation frost. The explanation for this apparent anomaly is that the layer of stagnant air (the boundary layer) over the leaf is thicker towards the centre than at the edges. The stagnant air retards the flow of water vapour to the leaf surface so ice forms preferentially where the layer is thinner (at the leaf edges).

The cooling of eucalyptus leaves below air temperature in a frost is shown clearly in Figure 6.3, from a study in Canberra, Australia in winter 1984 (Leuning & Cremer 1988). Small leaves were about 2˚C cooler than the air (leaf sizes were not stated) and the large leaves about 3˚C cooler. The centres of large leaves were 0.5 to 1.5˚C cooler than the tips but small leaves had more uniform temperature distribution. Horizontal leaves were 0.2 to 1.5˚C cooler than vertical leaves at the same height. Leaf and air temperature tended to be the same close to the surface but the leaves more than 100mm above ground were as much as 3˚C cooler than the air surrounding them.

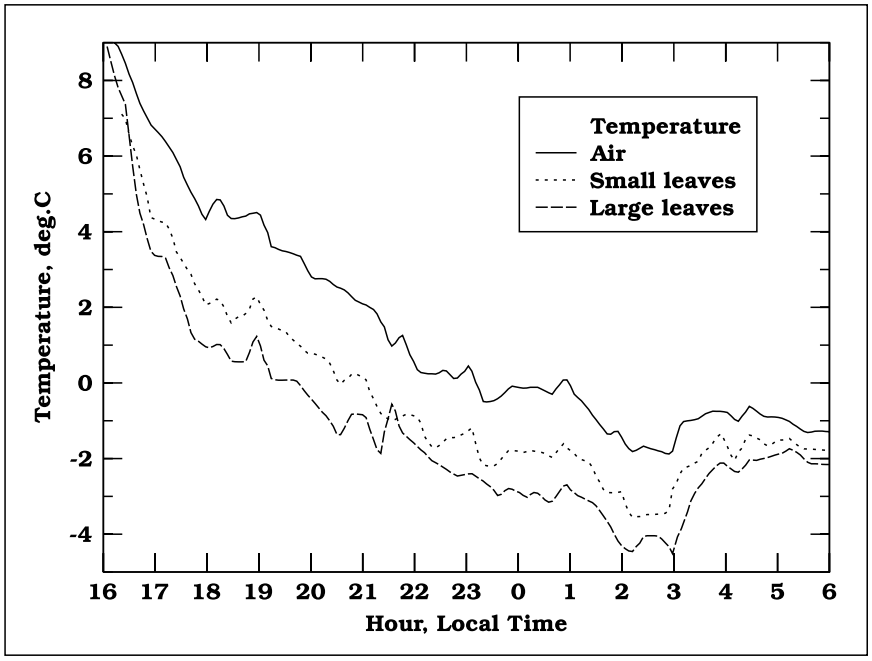

FIGURE 6.3. Temperature of the air, small and large eucalyptus leaves 100mm above grass in a radiation frost, showing that the leaves cool further than the surrounding air, and that large leaves (about 48mm wide) cool further than small leaves (about 10mm wide). (After Leuning and Cremer).

MODELLING CROP HEAT FLOW

Modelling the heat flow at the surface of a crop in a radiation frost shows the factors that may need to be modified by a frost protection strategy. The relationship between crop temperature and surroundings can be established by assuming an equilibrium heat flow and constant temperature. The radiant heat flow from a crop surface at night, to a first approximation, has to be balanced by the sensible heat flow and the dewfall from the air to the crop, i.e.

$$Qr = Qc + Qe \text{ (at equilibrium there is no net flow)}$$

where Qr = radiant heat flux, positive for flow out of the crop surface (W/m^2)

Qc = sensible heat flux, positive for air-to-crop flow (W/m^2)

and Qe = latent heat flux, positive for dewfall (W/m^2)

With a clear sky at night, the effective sky emissivity is about 0.74, making the sky temperature about 15°C cooler than the crop, radiant flux is positive (outward), the crop cools below air temperature, sensible heat flows from air to crop, and when the crop temperature is below the dew point latent heat flows from air to crop as dew forms on the surface, Qc and Qe are positive quantities.

Using the convention that the radiant flux Qr is assigned to the area of the upper crop surface only, it is about equal to the net radiation from the ground, or 40 to 100W/m^2. The radiation through both upper and lower crop surfaces changes by about 5W/m^2 for each

degree that the crop is made warmer than its surroundings, increasing the radiant flux Qr by 10W/m^2 assuming it all flows from the upper surface.

A simple approximation of sufficient accuracy for estimating the sensible heat flux, Qc, between air and crop in a radiation frost, over the range of wind speed and temperature of interest, may be obtained by modifying the general formula for sensible heat to

Qc = hc*(Tac-Tc)
where hc = sensible heat transfer coefficient
is a function of crop size
Tac = air temperature at crop height (˚C)
and Tc = crop surface temperature (˚C)

Assuming that the sensible heat transfer coefficient, hc, for flow between the air and a bud or leaf at night is approximately proportional to the square root of wind speed and inversely proportional to the square root of its size (Jones 1992), and therefore related to the area of the upper surface, we have

hc = Cc*√(u/d)
where d = the characteristic dimension of the leaf or bud
(may generally be taken as the diameter in metres)
u = wind speed at crop height (m/s)
and Cc = a constant related to the stage of development of
the bud or size of leaf (4<=Cc<=7.5)

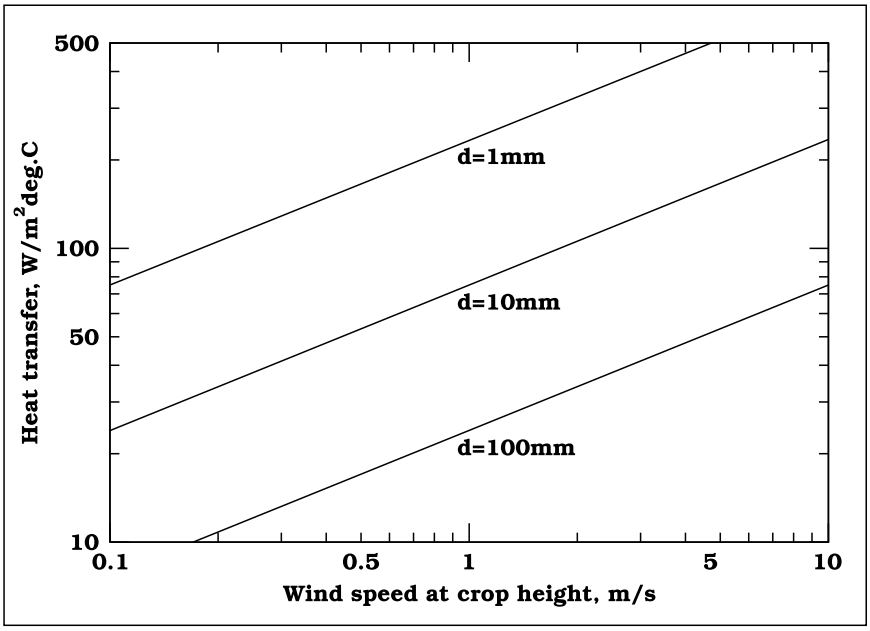

FIGURE 6.4. Heat transfer between air and a crop surface during temperature inversion conditions at night, for a difference of 1˚C between air temperature adjacent to the crop and crop surface temperature, and wind speed at crop height above the ground, and for a range of 'characteristic' dimensions appropriate to fruits, leaves, buds, and stems.

Figure 6.4 may be used to estimate the value of hc for selected crop surfaces over the range of wind speed from that in radiation frost (0.1 to 1m/s) to fresh breeze (10m/s), using the maximum value of Cc of 7.5W/m^2/°C, to match observations reported in the literature for unprotected crop surfaces. When sprinkled buds are covered in ice the value of Cc reduces as the ice builds up and may fall to about 4W/m^2/°C after prolonged sprinkling (Hamer 1986).

The latent heat flux Qe to the crop is obtained from the relationship between sensible and latent heat

$$Qe = 0.77*hc*(Tdp-Tc)$$

where Tdp = dew point (°C)
and Tc = crop surface temperature (°C)

WORKED EXAMPLES

The heat balance at the ground surface late at night in a hard spring frost may be calculated using the approximations suggested above, for comparison with the conditions resulting when various frost control systems are used to protect a model apple bud in such a frost. The screen temperature is assumed to be Ts = -4.5°C (268.65K), surface temperature is Tg = -7.5°C (265.65K), dew point temperature is Tdp = -4.5°C (268.65K), clear sky emissivity is Es = 0.71, surface emissivity is Eg = 0.95 and wind speed is u = 0.5m/s at screen height (1.3m). Assuming an equilibrium with constant temperatures and no net heat flow to or from the surface, the net radiation Qrn = 59W/m^2, upward from the surface to the sky may be balanced by a downward convection of sensible heat from the air Qc = 14W/m^2, latent heat from the frost Qe = 11W/m^2, and an upward flux through the soil Qg = 34W/m^2.

Using the approximations for a dew-covered apple bud with a diameter of 10mm, at screen height 1.3m above ground, we find that it will cool below the temperature of the surrounding air until the heat lost by radiation is balanced by the inflow of sensible and latent heat. The temperature to which the bud must fall for the equation to balance is Tc = -5.32°C (267.83K). The bud cools below dew point until the radiant flux from the bud Qr = 76.5W/m^2, is balanced by sensible heat from the air Qc = 43.2W/m^2, and latent heat from the dew Qe = 33.3W/m^2. At equilibrium the bud is 0.82°C below the temperature of the surrounding air.

PROTECTED CROP HEAT BALANCE

Frost protection methods must reduce the radiant heat loss from a crop, increase the sensible and latent heat gain from the surrounding air to the crop, or they must supply heat either directly to the crop or to its surroundings.

Heating only the crop, although hardly a practical frost protection technique would require the minimum amount of energy to be supplied. This scenario may be modelled by adding another term Qs, to the heat balance equation, which becomes

$$Qr = Qc+Qe+Qs$$

where Qs = heat supplied directly to the crop

The radiant heat loss Qr, typically 40 to 100 watts for each square metre of the upper surface, increases by about 10W/m^2 for each degree that the crop is warmed. The air-to-crop sensible heat flux Qc falls to zero when the crop is heated to air temperature, and reverses when the crop is heated above air temperature. The crop loses up to perhaps 100W/m^2 to the air by convection for each degree that it is heated above air temperature. If the unprotected crop is one degree below the temperature of the surrounding air and is heated two degrees, one degree above the temperature of the surrounding air, the source must provide all the heat lost by radiation plus that lost by convection to the air, requiring Qs to be of the order of 180W for each square metre of the upper crop surface. The latent heat flux Qe is zero when the crop temperature is equal to the dew point. If the method wets the crop surface and holds it above the dew point it will also have to provide for the heat lost by evaporation.

CHAPTER SEVEN

FROST PROTECTION

INTRODUCTION

Of the order of 80% of climate-caused agricultural losses in the USA between 1940 and 1990 were due to frost (Worthington 1993). It has been estimated that the value of this loss was 2.3% of the total crop value, and that the minimum insurance premium necessary to provide for all losses due to hail and frost would be of this order, provided all growers contributed to an insurance fund.

Plants matched to climate are rarely injured by frost. Low productivity and several plant diseases result from minor frost damage. Frost damage to crops is not always catastrophic; sometimes fruit is merely blemished; russet in apples results from frost damage before full bloom. A moderate expenditure on frost fighting may ensure that the maximum quantity of first grade fruit can be harvested every year. The reward is twofold: maintenance of fruit quality and maximum return on investment.

When frosts cause severe or frequent crop injury some form of frost fighting or control may be necessary to permit a particular crop to be grown, to reduce or eliminate loss or to prevent freezing injury to plant tissues. The methods are 'passive' when they are permanently in place and require no further attention when frost occurs; they are 'active' if they are used only when frost is present. Frost is not the only cause of freezing damage to crops. Unseasonable snowfalls can result in sub-zero temperatures during critical periods. Frost fighting equipment or methods may be needed to protect crops from snow damage, from katabatic winds, and advection frosts. The only absolutely reliable frost protection methods are those that supply sufficient heat directly to the crop to raise its temperature above that causing damage. The other methods, with variable reliability, modify the crop or environment in some way so that the crop is not cooled to a damaging temperature.

SITE SELECTION

A central agency may be able to provide an atlas identifying suitable growing areas for particular crops based on long-term meteorological records and extensive mobile temperature surveys on clear calm nights. The Association of British Columbia Grape Growers has published such an atlas (Agriculture Canada 1984). It included topographical maps of the Okanagan and Similkameen Valleys, showing growing degree-days, autumn freeze risk and soil groups, plus relevant tables and discussion.

Four classes of autumn freeze risk were defined, based on vine damage observed during the 1981 and 1982 autumns. They are shown in Table 7.1, below.

CLASS	FREEZE RISK	FREQUENCY OF DAMAGING FROST
1	0 to 10%	0 to 1 years in 10 years
2	10 to 30%	1 to 3 years in 10 years
3	30 to 50%	3 to 5 years in 10 years
4	50 to 100%	5 to 10 years in 10 years

Autumn and spring frost risk for Kiwifruit has been mapped for the Saanich Peninsula of Vancouver Island, Canada (Pyke et al 1989). Air temperature measured 1.2m above ground in front of a roving vehicle was compared with that at four fixed stations on about 33 clear nights in 1986, 87 and 88. Isotherms were drawn for 1˚C differences. Valley floors were coldest, higher elevations and sloping lands were up to 6˚C warmer than valley floors. The probability of a frost of given severity for any location could be calculated using the map and an accompanying table and diagram based on frost probability at a reference site.

Careful selection of orchard sites in rolling country will minimise frost risk. Frost pockets can be avoided and frost-tender crops confined to ridges or higher ground. Good cold air drainage can be assured by removing air dams such as fences and hedges. 'Micro Site Evaluation' may be used to establish the frost climate of a proposed orchard or to suggest ways to modify an existing arrangement. Temperature is measured in as many places as possible in the area of interest for as many frosts as possible until a consistent picture emerges. Air temperature at screen height is the simplest measure. It can be read from a thermometer mounted in front of a roving vehicle or on a hand-held thermometer. Minimum temperatures can be obtained from several minimum thermometers distributed across the area. The measurements may be compared with those from the nearest one or two meteorological stations to establish the likely long-term minimum temperature statistics for the site.

Frost fighting is difficult in small orchards. At the other end of the scale is the 'infinite' orchard where it is comparatively easy. A large unobstructed site in the centre of a very large flat level area, with reasonably uniform vegetation, may be considered to be an 'infinite' orchard. The edge of the orchard would be so far upwind that 'edge effects' due to wind drift would become insignificant over much of the orchard. Small areas require proportionally more energy per unit area for frost protection than do large areas because of wind drift and wastage at the edges.

PROBABILITY OF FROST DAMAGE

The best frost protection strategy is good site selection, but it may be unrealistic to assume that once a suitable site has been chosen no further frost damage will occur. A good starting point would be to establish how often a frost might be expected to damage the proposed crop in the chosen situation. The minimum overnight temperature to be expected once in a lifetime in a given month at the chosen site may sometimes be established from minimum temperature records or from a frost atlas. In a country such as New Zealand the minimum occurring only once every 30 to 100 years is about 4˚C colder than the average monthly minimum temperature.

In the absence of temperature records local experience may suggest for example that on average three frosts a year will damage the crop unacceptably. Economic or cultural considerations may suggest that frost damage once every ten years would be acceptable. Raising the crop temperature by one degree may approximately halve the likelihood of frost damage and up to perhaps four degrees of protection may be required to reduce the risk significantly. To achieve this level of protection from an active frost protection system alone would be very expensive. It would pay to investigate the possibility of using as many passive techniques as possible to lessen the demands on the active system.

MEASUREMENTS AND FORECASTS FOR FROST CONTROL

Reliable weather and frost forecasts are essential to good crop management during the frost-fighting season. A general area forecast is often made about sunset and may include

an estimate of the probability of frost at a particular place of interest. Controlling frost-fighting equipment according to general area forecasts based on measurements made before sunset would be inefficient and wasteful. It would often provide protection when none was needed. Much better would be a continuously updated service covering a small specific area such as the Yakima Valley, Washington, USA. Radio and television stations at Yakima used to broadcast throughout the night regularly updated temperature and humidity forecasts (Stewart et al 1984). Daily frost forecasts may be available on the Internet (Clearwest 2000).

In the absence of a reliable specific area forecast service it may be necessary to make measurements at the orchard that can be used to predict overnight temperature and to control the frost fighting equipment. The forecast should show impending danger with sufficient warning for action to be taken when necessary. Instruments are available for making all the measurements necessary for accurate frost prediction for an hour or so ahead. Readings must be made regularly and elaborate calculations may be required to make the forecast. The forecast would need to be updated at least hourly, and could be made completely automatic, under the control of a personal computer. A graph of temperatures of interest (such as screen or grass) could be displayed on a monitor screen along with the predicted temperature curve for the next few hours. Alarm temperatures could be set and also indicated on the screen, and the frost control equipment could be activated at the appropriate time. The efficiency of the frost fighting system could also be monitored on the same computer using data from strategically placed temperature sensors. The 'worst case' forecast must assume that the sky is about to clear or remains clear. On no account should forecasting for more than a few hours ahead be other than 'worst case', assuming that the sky is clear, or will clear immediately, and will stay clear, and wind speed will be low.

TEMPERATURE MEASUREMENT

Air temperature is the most commonly measured meteorological variable for frost control. It can be measured accurately and more reliably than surface temperature or the temperature of some part of a crop, say leaf temperature. The main precaution is to prevent radiation errors where the reading may be several degrees too high in sunlight or a few degrees too low at night. Air temperature measurement at crop height has generally been found to be the most useful aid in active frost fighting. Temperature fall toward a dangerous level or to a preset alarm level can be detected and used to start up a sprinkler system or to trigger the alarm at some remote place. Measurement at two sites, one inside the area to be protected and one outside, may indicate the effectiveness of the frost fighting technique or indicate any failure.

Comparing the air temperature at two heights, say 1.3 and 10m above ground, indicates unambiguously the cumulative effect of all the factors controlling radiation frost. Regular or continuous measurement of temperature at these heights at a common site may be used to follow and forecast frost, or to indicate whether a wind machine or helicopter will be able to give the protection desired. A strong temperature inversion, say 4°C, between air temperature measured at the two heights results from a clear sky and low wind speed. Cooling will be rapid and likely to be 'worst-case'. A weak temperature inversion with only one degree difference will result from a cloudy sky or a significant wind. There may be little danger of frost damage in the next few hours unless the wind is below freezing (a 'freeze') or the clouds suddenly disperse.

Well-designed thermometers will measure the required temperature with an error approaching 0.1°C, adequate for frost control. Thermometers with errors in excess of 0.5°C should not be used.

HUMIDITY AND NET RADIATION MEASUREMENT

Radiation frost is caused by the outwards radiation of infrared heat from the surface towards the sky. Some of the heat is absorbed by the greenhouse gases in the air and is re-radiated back to the surface. A dry atmosphere re-radiates less heat back to the surface than a humid atmosphere, so the surface cools more quickly when the air is drier, and the dew point lower, than when the air is wetter, and the dew point higher. Frost forecasting models use either atmospheric humidity or dew point as input, often using a measurement made in the afternoon or about sunset. With regular and careful maintenance 'wet' and 'dry' thermometers are reliable and very accurate practical devices for measuring atmospheric humidity and dew point. When dew point is required it is usually obtained from a table such as Table 7.2 of wet and dry bulb temperatures, or a table like Table 7.3 of dry bulb temperatures and relative humidity. More sophisticated devices that provide humidity data automatically to a computer are also available. When the sky is clear all night a clear-sky model with the appropriate atmospheric humidity will give excellent temperature prediction.

Net radiation may be measured continuously with a radiometer, an instrument that measures the difference in temperature between the upwards-facing black surface and the downwards-facing black surface of a thin horizontal plate 'sandwich' about a metre above the ground, with due allowance for the effect of wind in the surrounding air. A radiometer that measures both net radiation and temperature allows forecasts to be revised as the night proceeds. When clouds are present they re-radiate much more heat back to the surface than does the clear air, so net radiation is reduced and cooling is slowed. The unpredictability of cloud cover and the resulting unpredictability of the cooling is the single most difficult aspect of radiation frost forecasting.

TABLE 7.2:

DRY BULB	WET BULB DEPRESSION, DEGREES CELSIUS.							
DEG. C.	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
	DEWPOINT TEMPERATURE, DEGREES CELSIUS.							
20.0	18.5	16.9	15.3	13.5	11.6	9.5	7.5	5.0
18.0	16.5	14.8	13.0	11.2	9.1	6.9	4.4	1.6
16.0	14.4	12.6	10.8	8.8	6.6	4.2	1.4	-1.6
14.0	12.3	10.5	8.5	6.3	4.0	1.2	-1.7	-5.2
12.0	10.2	8.3	6.2	3.8	1.1	-1.7	-5.1	-9.4
10.0	8.1	6.0	3.7	1.2	-1.6	-4.8	-8.9	-14.8
8.0	6.0	3.7	1.3	-1.4	-4.4	-8.3	-13.7	-23.2
6.0	3.8	1.4	-1.1	-4.0	-7.7	-12.5	-21.0	
4.0	1.7	-0.8	-3.5	-6.9	-11.5	-18.8		
2.0	-0.4	-3.0	-6.2	-10.4	-16.6			
0.0	-2.5	-5.3	-9.3	-14.7	-24.0			
-2.0	-4.8	-8.2	-12.8	-20.0				
-4.0	-7.1	-11.1	-16.8					
-6.0	-9.5	-14.2	-21.9					
-8.0	-12.0	-17.7						
-10.0	-14.6	-21.9						

TABLE 7.3:

DRYBULB	RELATIVE HUMIDITY, PERCENT.								
DEG. C.	90.0	80.0	70.0	60.0	50.0	40.0	30.0	20.0	10.0
	DEWPOINT TEMPERATURE, DEGREES CELSIUS.								
20.0	18.3	16.4	14.4	12.0	9.3	6.0	2.0	-3.2	-11.0
18.0	16.3	14.5	12.4	10.1	7.4	4.2	0.1	-4.7	-13.0
16.0	14.4	12.5	10.5	8.3	5.6	2.5	-1.3	-6.3	-13.7
14.0	12.4	10.6	8.6	6.4	3.8	0.6	-2.9	-7.7	-15.5
12.0	10.5	8.6	6.8	4.5	2.0	-1.0	-4.3	-9.2	-16.5
10.0	8.5	6.8	4.7	2.5	0.1	-2.6	-5.9	-11.0	-18.5
8.0	6.4	4.7	2.8	0.6	-1.6	-4.3	-7.7	-12.3	-19.7
6.0	4.5	2.8	0.9	-1.1	-3.2	-5.9	-9.2	-13.7	-21.2
4.0	2.5	0.9	-0.8	-2.7	-4.9	-7.5	-10.8	-15.2	-22.6
2.0	0.5	-1.0	-2.6	-4.4	-6.5	-9.1	-12.4	-16.8	-24.0
0.0	-1.3	-2.7	-4.3	-6.1	-8.2	-10.8	-14.0	-18.3	-25.4
-2.0	-3.2	-4.7	-6.2	-8.0	-10.1	-12.6	-15.7	-20.0	
-4.0	-5.2	-6.6	-8.2	-10.0	-11.9	-14.4	-17.5	-21.7	
-6.0	-7.2	-8.6	-10.1	-11.8	-13.9	-16.3	-19.5	-23.4	
-8.0	-9.2	-10.5	-12.0	-13.7	-15.7	-18.1	-21.1		
-10.0	-11.2	-12.5	-13.9	-15.6	-17.6	-20.0			

FORECASTING WITH NEWTON'S LAW OF COOLING

The only measurements required for Newton's law forecasting with a computer are air temperature at crop or screen height. Additional temperature measurements can be made to indicate the strength of the temperature inversion, the presence of clouds, and the effect of wind. The temperature of a second thermometer attached to a small horizontal metal disk with its upper blackened surface exposed to the sky and its lower surface thermally insulated, placed at the same height as the air thermometer, indicates approximately the temperature of the upper surfaces of the crop that are exposed to the sky. Comparing these two temperatures gives an approximation to net radiation and will show when clouds are present. With a clear sky at night the black disk will be about two to four degrees cooler than the air and when clouds appear will be closer to the air temperature. The temperature at the ground surface will also be similar to that of the disk. (In sunlight the disk will be perhaps twenty degrees warmer than the air and when it is cloudy closer to air temperature.)

The thermometers used for these measurements will need to give an output capable of being read by a computer. They can both be contained within a common sensor that can be mounted on a conveniently placed post with a wire or radio link back to the computer. A suitable sensor will be a short length of foam-filled white plastics tube a few centimetres diameter with the top covered by a metal cap painted matt black that is slightly domed to allow rain and dew to run off. Attached to the lower surface of the cap is an electrical thermometer. The tube is sealed about a centimetre above its lower end to make a space where an electrical thermometer that measures the air temperature is placed. It may be combined with a humidity sensor so that the dew point may be known well before sunset to give plenty of warning of an impending frost. The radiation screening of the air thermometer requires care to prevent errors from sunshine during the day and about sunset and sunrise. The upper centimetre or so of the plastics tube should be exposed but the rest should be enclosed inside two concentric aluminium or stainless steel tubes with about 5 to 10mm air spaces between, and an aluminium or stainless steel disk should be attached below the air thermometer. Air should be able to pass freely between the lower disk and the cavity at the lower end of the plastics tube where the air thermometer is mounted.

FROST PROTECTION METHODS

Many methods have been used to protect valuable crops from frost. Techniques have been developed over centuries but the best method for a given situation may depend on many factors that should be weighed carefully before a decision is made. Every situation will be different to all others so making a satisfactory choice may not be straightforward. The overriding factors for a commercial venture must be reliability and maximisation of profit, but for a prized garden specimen survival may be all that matters.

The danger of frost injury can be lessened by passive techniques such as increasing the crop frost resistance biologically or chemically. Strains or cultivars may be selected, grafted or genetically engineered to give increased frost resistance. Increased frost hardiness can be a useful side effect when growth-regulating chemicals and bactericides are used. Careful use of fertilisers can also improve frost resistance.

The type of frost or cold weather event affects the choice of a frost protection method. Simple radiation frosts with still air on flat land usually may be effectively combated by any one active or passive, direct or indirect method. Protection from katabatic wind frosts may require direct heating of the crop and possibly the judicious placement of shelter. Advective freezes and unseasonable snowstorms may require direct crop heating to be maintained for days on end.

It may be necessary to choose between a technique that sometimes gives adequate crop protection and one that always succeeds. The only absolutely reliable methods are those that heat the crop directly. The others, with variable reliability, modify or heat the environment, making the surroundings warmer than the crop and hopefully maintaining it at a safe temperature.

ACTIVE FROST CONTROL

In a simple radiation frost, radiation from the crop to the sky and the ground will cause the crop to be colder than the surrounding air. Active frost protection measures either reduce the radiation loss, heat the crop or surroundings, or a combination of all three. They must take account of the close coupling between crop and air temperature. Introducing an artificial fog does much more than just reduce the radiant heat loss and can be (in principle but rarely in practice) a very effective frost fighting technique. Heating the surroundings may fail if the air cannot be maintained a few degrees above the critical temperature of the crop. Crop heating methods may fail if the crop temperature cannot be maintained a few degrees above that of the surrounding air.

Active frost control must be initiated when the crop temperature falls below a predetermined level and maintained until danger passes. The crop is warmed either by heating directly, or indirectly as a result of heating the surroundings. Fuel may be burned to heat the crop and surroundings, water may be sprayed on the crop or the ground to maintain the crop temperature near 0˚C, or wind machines may be used to redistribute atmospheric heat.

Burning fuel has been used for frost protection for at least two thousand years. It is the most expensive method but is still used when other systems would be inappropriate.

The lowest-cost method of heating is to sprinkle water directly on the crop. Provided that the sprinkling rate is sufficient to maintain a wet surface on the ice that builds up on the crop, the plant tissues will not cool below about -0.5˚C, and they will not be damaged by freezing, but in a protracted frost the ice load may break the limbs off trees. Crops have been safely held at -0˚C in frosts that would otherwise have cooled them to -7˚C.

Creating a breeze can increase the sensible and latent heat flow from air to crop. When wind machines or helicopters are used mixing with warmer air from aloft also warms the air passing the crop, and the heat passed to the crop is further increased. Crop temperature can be increased typically one to two degrees but rarely more than 3°C, and not above the surrounding air temperature, with wind machines and helicopters.

HIDDEN COSTS

The cost of active frost control is not limited to the orchardist. The method chosen will impinge directly on equipment, power, and water suppliers. Frost fighting consumes large amounts of energy in comparatively short times and the reticulation systems may have to be increased in capacity to cope. Electric power lines capable of providing power for pumps or wind machines of the order of 100kW are expensive. Where many units are installed the heavy-duty lines may have to go a great distance to the nearest substation. Irrigation schemes generally will not be able to provide running water in the volume required for frost control. Storage dams able to hold enough water for at least ten hours continuous frost fighting, and able to be refilled in the next 10 to 14 hours, may be required.

SHARING RESOURCES

There may be occasions when there may be good reasons for common use of resources. If the need for frost control is so minimal that the use of helicopters in place of fixed wind machines is viable a co-operative scheme may allow one helicopter to protect an area larger than a single orchard if the helicopter is used on two or more adjacent orchards on the same occasion.

RELIABILITY

Frost fighting machines must be reliable. Catastrophic failure of a single large machine may result in a total crop loss. Spreading the load between several smaller machines may increase reliability because not all are likely to fail simultaneously. Standby machines can also be small. For example a tractor with power takeoff may be able to be used to drive a pump or wind machine if the machine's own motor fails. There may also be cases where several small machines give more uniform protection over an area than does one large machine.

Thermostatic controls that trigger alarms, start and stop or vary the amount of protection from sprinkler systems, gas-fired heating systems or wind machines must be absolutely reliable and 'fail safe'. If the controller fails the alarm sounds or the equipment turns on at full power. Preventive maintenance including full-scale testing before and during the frost season is mandatory. A system that fails is useless.

SIDE EFFECTS

Frost control practices can have deleterious side effects. Pests and fungous diseases resulting from frost control can lower fruit quality. Water logging of the ground by sprinklers may result in root rot in poorly drained soils. Controlling the application rate of a sprinkler system to match frost severity will reduce side effects and save costs, water and fuel.

Early heating systems used ‘smudge pots’. The smoke from these open-topped burners delayed warming after sunrise, reduced visibility, and blackened ‘everything in sight’. The smoke had no beneficial effect whatsoever.

Second grade fruit may result from excessive rubbing when wind machines are used to protect crops such as Kiwifruit. Noise from wind machines, helicopters or pump motors may disturb neighbours, keeping them awake for hours. Unsatisfactory water with sprinkler frost control may stain fruit reducing it to second grade.

CHAPTER EIGHT

BIOLOGICAL AND CHEMICAL FROST CONTROL

INTRODUCTION

The biological and chemical methods of frost protection that reduce the frost sensitivity of crops are usually 'passive' because no special action is required when a frost occurs. The response to frost has been either temporarily or permanently modified by a suitable technique such as matching crop variety to climate, altering plant super cooling, modifying the effect of ice nucleating particles, or by chemical control of dormancy, bud break or ripening. The methods are passive in the sense that they are applied hours, days, or months before an expected frost.

REDUCED SUPER COOLING

When ice is nucleated on a plant surface in a frost it usually propagates into the tissues and may damage the plant. New growth rarely remains unfrozen and undamaged when it is cooled more than a few degrees below 0˚C. Older, hardened growth can survive surface and extra cellular ice provided nucleation occurs at a sufficiently high temperature. If the frost protection technique ensures that freezing is initiated as close as possible to 0˚C even new growth and frost tender plants such as potatoes can sometimes survive frost without appreciable damage. On the other hand super cooled material freezes very rapidly when nucleated and damage can result from ice formed from water that has had insufficient time to move to the extra cellular spaces before freezing.

Freezing has been initiated above -1˚C by adding suitable substances to water. Acetoacetanilide and fluorophlogopite, a fluorine mica, were found to be effective in one per cent suspensions. They nucleated ice above -1˚C, slightly higher than the nucleating temperature of the best-known nucleating agent at the time, silver iodide (Shen et al 1977).

Water-soluble alcohols are effective antifreeze agents, but the hydrophilic head groups of mono layers of long-chain aliphatic alcohols of the series $C_n H_{2n+1}OH$ can nucleate water drops at temperatures near 0˚C. The nucleation temperature increases with n, asymptotically approaching 0˚C for n odd and greater than 29, and -8˚C for n even and greater than 20 (Gavish et al 1990). Reduced super cooling that results from induced nucleation by such mono layers may be an effective frost protection strategy for some crops but wetting the plants with them prior to a frost to induce freezing may be a hazardous method of frost protection. The technique is quite distinct from the very successful active sprinkling method where continuous freezing maintains crop temperature between 0 and -1˚C.

INCREASED SUPER COOLING

When ice nucleation is prevented plants can remain super cooled and unfrozen for the frost duration. Super cooling can be increased so that freezing and frost damage is avoided, if the particles that initiate ice formation can be removed from a crop surface, or in some way modified, before an otherwise damaging frost. The atmospheric particles responsible for initiation of freezing on plants were eventually found to be the same as those causing ice nucleation in clouds. Identification of the cloud seeding particles was an important part of

extensive rain making experiments. Many possible sources were identified over several decades of research (Schnell and Vali 1976).

Extraterrestrial meteoritic material was found to be a source of effective ice nucleating particles below -15˚C. The oceans and volcanoes were poor sources and man-made aerosols did not contribute significantly to atmospheric ice nuclei. Inorganic soil particles, mainly clays, were found at the centres of most snowflakes, but they did not appear to be capable of nucleating ice above -10˚C.

It appeared that the nuclei capable of initiating freezing on many plants at temperatures above about -10˚C were the by-products of active bacterial decomposition of organic material. It was established that the ice nucleating particles could be produced by, or in association with, the epiphytic bacterium Pseudomonas syringae, a widely distributed plant pathogen.

Ice nucleation on woody plants such as Prunus species appears to be different to that on the frost-tender herbaceous annuals where it is related to bacterial population (Proebsting & Gross 1988). It was concluded on the basis of six years work at Prosser, Washington USA that there is some unknown feature of the surface of the woody stems of Prunus that allows ice nucleation between -0.6 and -2.6˚C irrespective of bacterial population on the surface.

The ice nucleating property of Prunus wood develops about the time stems reach maturity in midsummer then remains relatively constant. The substance is apparently not a protein. Prolonged soaking in water deactivates it indicating a change in conformation on hydration.

The Prosser experiments suggested that ice nucleation at about -2˚C on the stems of apple trees before the 'frost-sensitive' stage was advantageous by preventing rapid growth of ice within the tissues. At that time the buds were able to super cool even though the stems were frozen. Later, following anthesis (opening of flower buds) ice on the stems is able to nucleate ice in the buds and they are killed. Identification and deactivation of the nuclei associated with woody surfaces may lead to a method of frost protection by increased super cooling. Super cooling should be avoided before the flowers open but encouraged after. Frost protection strategy should therefore change at anthesis.

ICE NUCLEATING BACTERIA

At least four species of bacterium are associated with ice nucleation on plants at temperatures above -10˚C. They are Pseudomonas syringae, Pseudomonas fluorescens, Pseudomonas viridiflava and Erwinia herbicola. Pseudomonas bacteria can grow at -10˚C and are the major cause of spoilage of pasteurised milk stored at 4 to 7˚C.

Bacteria such as Pseudomonas syringae are found on the surfaces of many plants. Populations are low in summer and winter but may be very high for a few weeks in autumn and spring. They are normally epiphytic, living on the plants without causing injury, but they become pathogenic and proliferate quickly following tissue damage such as that caused by frost. Pseudomonas syringae is a known pathogen of barley following midwinter frost. Leaf spotting and tip chlorosis follow necrotic lesions and tissue discolouration in the lower crown and roots. Degeneration spreads from freeze-damaged tissues to adjacent uninjured material (Olien and Smith 1981).

Bacterial blast, also known as 'sour sap', 'dieback' and 'gummosis', is a seasonal problem on several plant species, being most prevalent in autumn and spring and following frosts. Tip dieback in nectarines due to Pseudomonas syringae in New Zealand is associated with frosts in autumn before the trees have hardened. In spring, wilting of branches and trees, tip dieback and nodal infection follow bud break. All disease activity ceases during summer, but dieback has sometimes progressed through winter (Young 1987).

Pseudomonas syringae is a gram-negative rod-shaped cell about 2um long and 0.4um radius, much too large to be an active ice-nucleating particle at -2˚C (Vali et al 1976). The ice nucleating particles are made of a protein that is synthesised by the bacterium and excreted at low temperature as disk-shaped patches that grow on the surface of the bacterium. Disc diameter and height grow together up to 7.5 nanometres. The maximum height appears to be about 7.5nm but the diameter can be up to 235 nanometres. A nucleator active at -1˚C would be an aggregate of 558 monomers of 150,000Da (83,700,000Da) and have a diameter of 90 nanometres (Burke & Lindow 1990).

ICE NUCLEATION INHIBITORS

The implication for frost damage control is that reduction of bacterial populations to low levels may increase super cooling and confer several degrees of protection to otherwise frost tender plants. One method is to kill the resident bacteria before the new growth in spring with bactericides such as Bordeaux or cupric hydroxide ('Kocide 101'). Trees sprayed with copper bactericides before bud break have been reported many times to have set a significantly different amount of fruit than untreated trees. The bactericides are effective against Pseudomonas syringae and have given frost protection down to -9˚C. The method is potentially hazardous if the temperature falls so low that ice nucleation occurs and causes non-equilibrium freezing of the super cooled plant material. Bactericides should be applied at least two days before anticipated frosts and may be effective for a week or two, but sprays applied after bud break can be toxic to plants such as Kiwifruit.

Streptomycin sulphate 150ppm and oxytetracycline 100ppm spray have been used weekly to maintain low bacterial populations on fruit trees in spring (Proebsting & Gross 1988).

An alternative to killing the bacteria is to reduce their ability to nucleate ice by spraying the crop prior to anticipated frosts. A mixture of urea, CH_4ON_2 and sodium carbonate, Na_2CO_3 has been found to be effective for up to ten days after application to almond trees in California, USA (Lindow & Connell 1984). It was found that urea was an effective frost protectant for fruit trees at Hastings, New Zealand but that great care should be taken to ensure that the urea is free of biuret, $C_2H_5N_3O_2$ to prevent fruit damage.

GENETIC ENGINEERING

An alternative method for preventing ice nucleation is to release antagonistic or genetically engineered bacteria to replace the natural strains. The gene responsible for ice nucleation in Pseudomonas syringae and Erwinia herbicola was isolated and parts of the protein sequenced. The gene was replaced with a defective one that cannot nucleate ice and a 'non-ice-nucleating' strain of bacterium was developed. A group at the University of California, USA, conducted field trials of chemically mutated bacteria, deficient in the protein causing ice nucleation, about 1980. They demonstrated that the deficient bacteria can confer several degrees of frost protection by displacing the naturally-occurring strains so that treated plants super cool without freezing (Budiansky 1983).

Proposals to field-test bacteria deficient in ice nucleating protein in 1983 were delayed following objections by people concerned that the genetically-engineered bacteria could have serious ecological consequences (David 1983). One suggestion was that the frost-resistant bacteria might disrupt the climate if they reached the upper atmosphere and altered the natural process of ice nucleation in clouds.

This would have been the first-ever release of genetically engineered organisms into the general environment. In defence of the proposal it was stated that the chemically mutated bacteria had lived only for about three months when released. They did not spread from the treated plants and were eventually replaced by the native population. Non-ice-nucleating bacteria occur naturally, apparently mutated non-specifically from the ice-nucleating species by ultraviolet light. It was suggested that the genetically engineered version would be safe because it deleted only one specific gene.

The United States Environmental Protection Agency declared the modified Pseudomonas syringae safe early in 1986. A mutant strain, named 'Frostban' by the manufacturers, was isolated from naturally occurring bacteria and was released onto a strawberry crop in California, USA in April 1986. The field test was claimed to have been a success and that Frostban reduced the likelihood of freezing by at least 1.1˚C (Bedbrook 1987).

The method proposed for frost control is to spray the mutant bacteria over susceptible trees just as the buds open. Then they will occupy the sites normally taken up by the natural bacteria and confer frost control until the danger period has passed.

CHEMICALLY INDUCED FROST RESISTANCE

Many chemicals are known to modify frost hardiness in plants. Frost protection has generally been a side effect to the main function of the chemicals and in some cases increased frost risk has resulted. There are few cases, with the exception of spraying with bactericide or antitranspirant chemicals, where frost protection is the only purpose for applying the chemicals to the plants.

ANTITRANSPIRANT SPRAYS

Several of the long-chain unsaturated dibasic fatty acids and their derivatives have been found to increase the permeability of plant cell membranes. They are also believed to inhibit stomata opening and reduce transpiration. Opinions vary as to whether they are useful for frost protection. Commercially available examples in California in 2000 included 'Frost Away', 'Wilt-Pruf', 'Frostgard', 'Frost Shield' and 'AntiStress'. AntiStress is a carbon chain polymer in a non-toxic acrylic base that dries on plant surfaces to a clear semi permeable elastic membrane that will stretch with plant growth. It biodegrades within one to two months. It has been claimed to give 2.2 to 2.7˚C "added protection from the freezing level of each plant species" (AntiStress 2000).

It has been claimed that peach, apple and pear flowers can be made frost resistant for several hours by spraying them with 0.001M-decenylsuccinic acid, $C_{14}H_{24}O_4$. Young beans grown for at least five days in vermiculite with 0.001M decenylsuccinic acid were resistant to a frost of -5˚C for an hour (Kuiper 1964). Decenylsuccinic acid was tested for two seasons on apples and plums in Central Otago, New Zealand. It was sprayed on the trees immediately before a frost and apparently reduced the percentage of blossoms killed. Up to 0.6˚C increased resistance was found but the technique was considered to be unsuitable for Central Otago where up to 3˚C resistance was required (Hewett 1971).

FERTILISERS

Phosphorus fertilisation has increased frost risk in some evergreens but has enhanced cold hardiness of winter wheat and rye (Alden & Herman 1971). Nitrogen fertilisation and

irrigation may be reduced in autumn to slow growth and hasten hardening but nitrogen fertilisers can alter the frost hardiness of crops by advancing spring growth. At Hastings, New Zealand a late spring frost in mid November 1996 substantially damaged juvenile grape vines that had been subjected to an active fertigation regime resulting in early bud break and vigorous growth, whereas neighbouring vineyards not so fertilised suffered little damage.

CHOLINE AND ETHANOLAMINE

Choline, $C_5H_{15}O_2N$ and ethanolamine, C_2H_7ON occur naturally in plants. They are necessary for the development of the phospholipid membranes surrounding the cells. Work in Hungary suggests that the membranes may be made frost resistant by increasing the supply of these two chemicals. Survival tests on wheat subjected to a disastrous frost in May 1981 showed 20 to 30% better survival of plants previously sprayed with choline and ethanolamine in activating agents (The Economist 1983).

TYROSINE

Tyrosine, $C_9H_{11}O_3N$ is a free aromatic amino acid widely distributed in ligneous forest plants. The suggestion that it may affect the frost resistance of young shoots was tested in Quebec, Canada in 1964 (Gagnon 1964). Two-year-old pot-grown spruce seedlings were watered daily for ten days with 2ml of 0.005M Tyrosine. They survived -10°C for 24 hours when untreated seedlings were killed.

GROWTH REGULATORS

The chemicals used to control second growth after pruning, root suckers, blossoming, or fruit set have sometimes been found to modify frost susceptibility enough for them to be useful for frost protection. Results have been variable, one suggestion being that in general those retarding growth increase frost resistance, those increasing growth reduce it.

ALAR

The plant growth retardant B995, B-Nine, or Alar, $C_6H_{12}N_2O_3$ has been reported to increase the hardening of some plants and decreased the cold-resistance of others (Levitt 1972).

ANA

Alpha-napthaleneacetic acid, NAA or Planofix, $C_{12}H_{10}O_2$ has been used to promote rooting of plant clippings, as a thinner of apples and recently for controlling unnecessary growth following winter pruning of apricots, apples and pears. It has been successfully used to delay blossoming of pears and in vineyards (Bagdonas et al 1978).

CCC

Chlorocholine chloride, CCC, or Cyclocel, $C_5H_{13}C_{l2}N$ is closely related to choline and can apparently assist plants with the synthesis of choline. CCC retards plant growth without injurious side effects and was shown to increase the frost-hardiness of tomato seedlings in a laboratory test in Torun, Poland in 1963-64. Seedlings grown in Knops nutrient solution

with 200ppm of CCC were much more freeze-resistant than untreated plants. Temperatures between -2 and -10°C caused over 92% mortality in plants from cotyledon to second pair of leaves but less than 28% mortality in treated plants (Michniewicz and Kentzer 1965).

A single spray of 1% CCC was applied to one-year-old pot-grown Williams' Bon Chretien pear trees in England in spring 1964. A year later at full bloom the trees were frozen to -3.5°C for 15 minutes. Of those sprayed with CCC 50% of the flowers were killed, compared with an 81% kill on unsprayed trees (Modlibowska 1965).

CCC has been mixed with lanolin paste and applied two weeks before bud-swell to nicks cut in the sides of two-year-old Kiwifruit vines in a glasshouse. A 30% increase in bud break resulted without any retarding effect on shoot growth (Henzell and Briscoe 1984). The CCC may have counteracted the erratic bud break normally resulting from too few frosts in winter.

ETHEPHON

Ethephon or ethryl, $C_2H_6ClO_3P$ is used both before and after harvest to generate ethylene and to accelerate ripening of fruits. It was proposed in 1973 that spraying fruit trees (sweet cherry) two months before leaf fall with 250 to 500mg/l of Ethephon would delay blossoming by three to five days (Proebsting and Mills 1973). This would reduce the probability of spring frost damage unless the delayed blossoms were more frost tender than unsprayed flowers. This Northern Hemisphere experience has shown that 200mg/l caused gummosis in peach; 500mg/l caused severe gummosis or killed peach and other stone fruit trees. Fruit set in plum has been reduced by applications of 250 and 500mg/l.

Ethephon was applied to fantasia nectarine trees at Himatangi, New Zealand in autumn 1985 in an attempt to reduce spring frost damage. The results were consistent with previously reported tests of blossom delay from applications of Ethephon to sweet and sour cherry, peach, plum and almond (Irving 1986, 1987). The trees were sprayed to runoff in April with Ethephon at 50, 200 or 400mg/l and blossoms were counted on branches at chest height during August and September. The most effective mixture in the New Zealand experiment was 200mg/l. Full bloom was delayed from 6 to 16 days and the blossoms on the treated trees experienced fewer frosts. From 50% blossoming they had only eight frosts compared with twelve for the controls. The frost sensitivity of the blossoms on the treated trees does not appear to have been compared with that of the untreated flowers, however the initial fruit set and crop yield (after thinning of fruitlets) were significantly increased. Crop yield was eight times greater on trees treated with Ethephon at 200mg/l. There is a suggestion that the fruit set in the untreated trees was low because the mean winter temperatures had been 1 to 2°C above normal. If this is so then a significant effect of the Ethephon may have been to give a better and more-uniform bud break, as well as a useful delay.

HYDROGEN CYANAMIDE

Hydrogen cyanamide, CH_2N_2 is used to give even bud break in Kiwifruit. A 1.5ha trial area in a 13ha Kiwifruit orchard at Pukekohe, New Zealand, was sprayed with 5l/ha of hydrogen cyanamide in 1988 (Wilson and Wilson 1989). Winter had been one of the mildest on record and bud break in untreated orchards was low and drawn out. Bud break in the treated area began at about the same time as on the end shoots of untreated vines but hydrogen cyanamide reduced bud break duration from 25 days to nine. Fifty per cent bud break occurred from 15 to 19 days earlier than on the other 11.5ha of the orchard. The plants were sprayed on

August 16, about a month before bud break started and pollination began on November 12, a week ahead of normal. A neighbouring block, sprayed on August 3, flowered four days ahead of those sprayed on August 16. The spring frost hazard on the untreated Kiwifruit vines in 1988 would have been reduced by late flowering to about half that of the vines induced to flower at a more 'normal' time by hydrogen cyanamide.

PP333

Paclobutrazol or Cultar, $C_{15}H_{20}ClN_3O$ is a triazole growth retardant that inhibits gibberellin synthesis. It was not found to affect bloom and harvest dates, nor flowering and fruit set of mature Sundrop apricot trees when applied as a trunk drench in a test in 1985 (Jacyna 1987). It advanced bloom of sweet cherry trees by 6 to 7 days and delayed harvest by about 4 days when applied as a soil drench in Winter (Jacyna et al 1989).

PLATE 4.1. Photograph showing the frost on a cabbage to be a collection of small, clearly separated, frozen dew droplets on an otherwise dry surface. (W. Ireland).

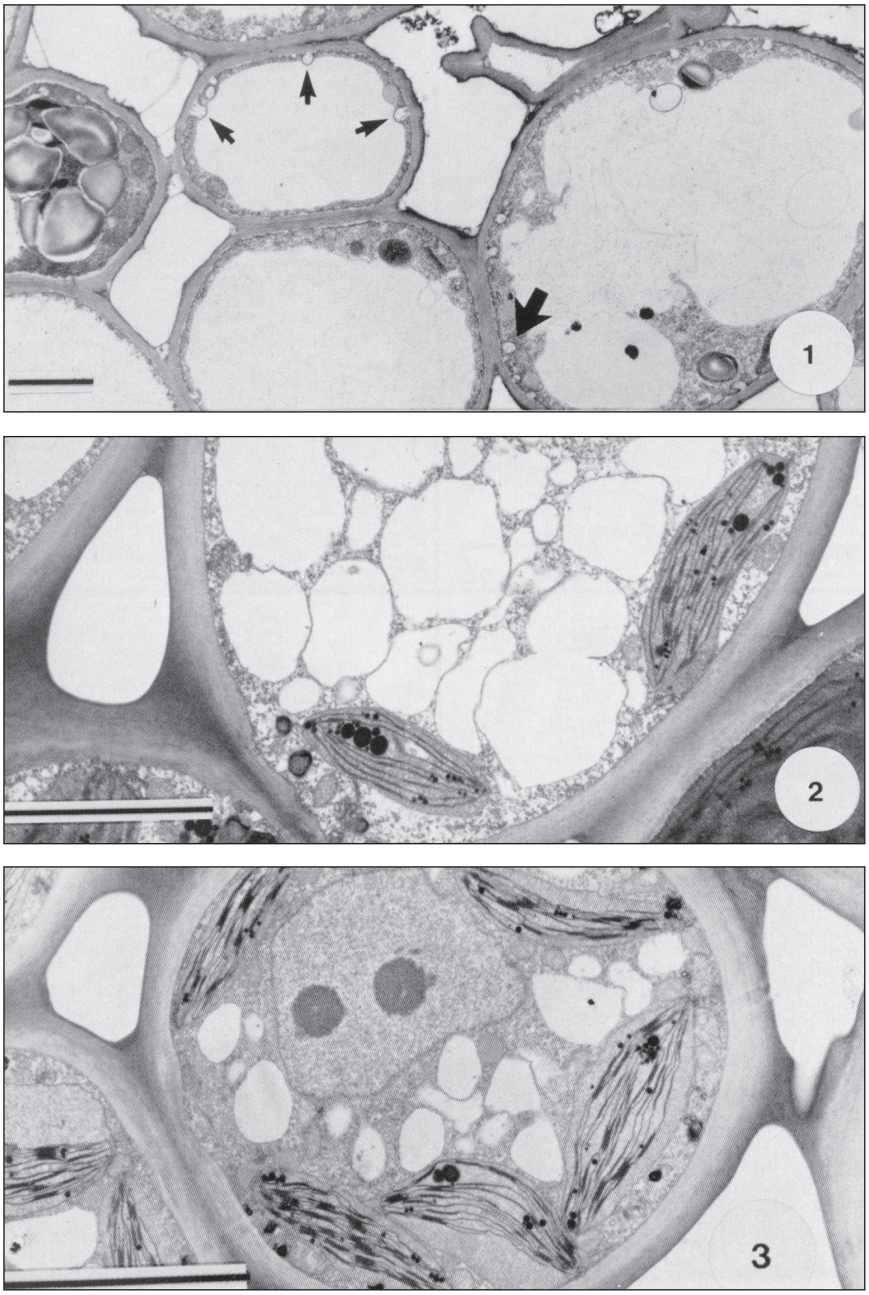

PLATE 4.2. Photomicrographs showing the changes in the structure of the bark cells of Peach with increasing hardiness. 1: Typical summer cells with large central vacuoles and thin bands of peripheral cytoplasm. 2: In autumn the central vacuoles break up. 3: At peak hardiness there is a centrally-located nucleus surrounded by many small vacuoles. (The arrows indicate irregularities in the plasma lemma, a feature of summer cell structure). Scales = 5um. (Wisniewski & Ashworth 1986).

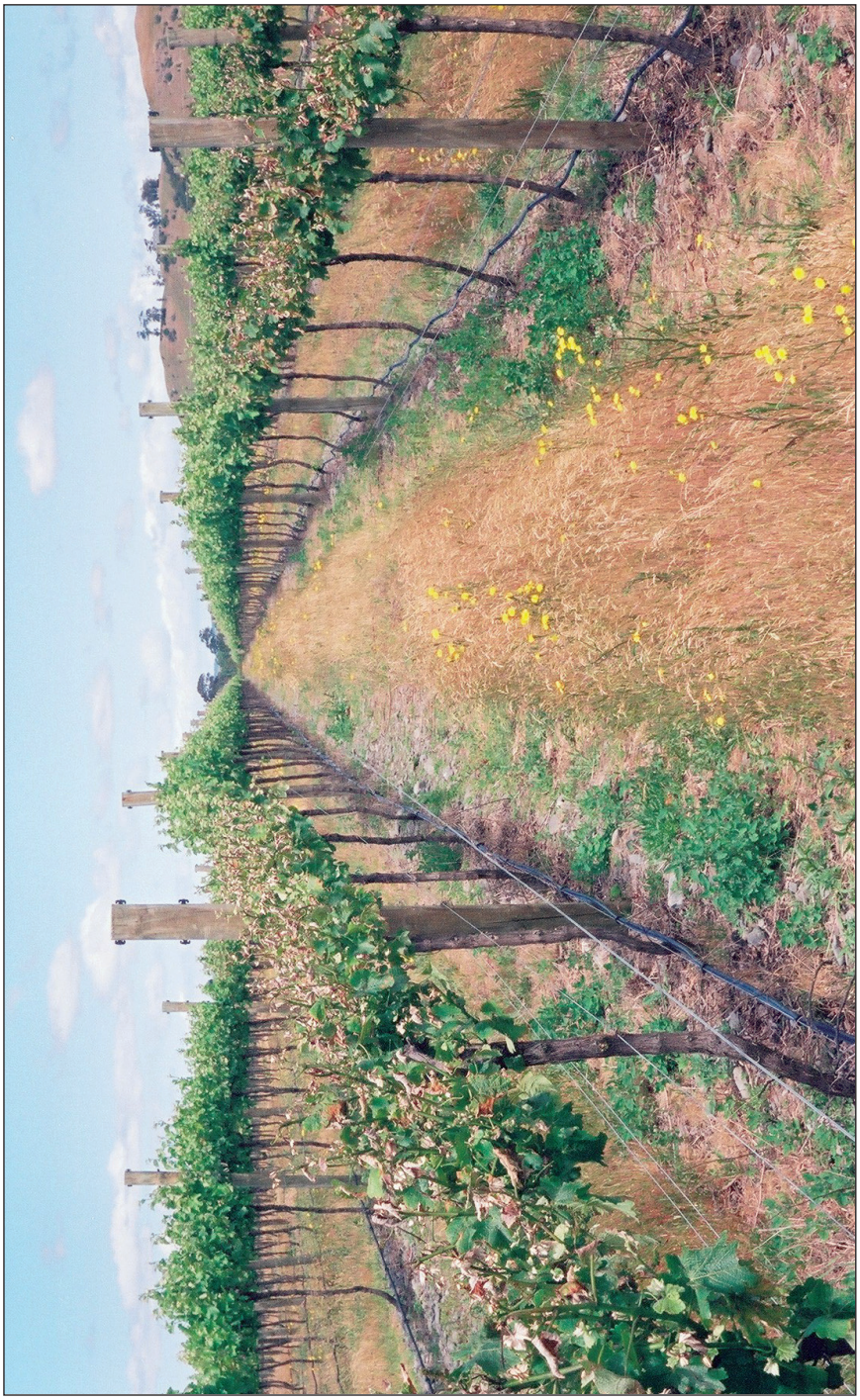

PLATE 5.1. Frost damage to juvenile grape vines in a hollow less than a metre deep in a generally level orchard at Hastings. (W. Ireland).

PLATE 5.2. Smoke plumes showing the effects of katabatic flow at Lower Hutt. In the centre of the valley a brisk wind carries the plumes almost horizontally, near the valley walls the plumes rise vertically. (W. Ireland).

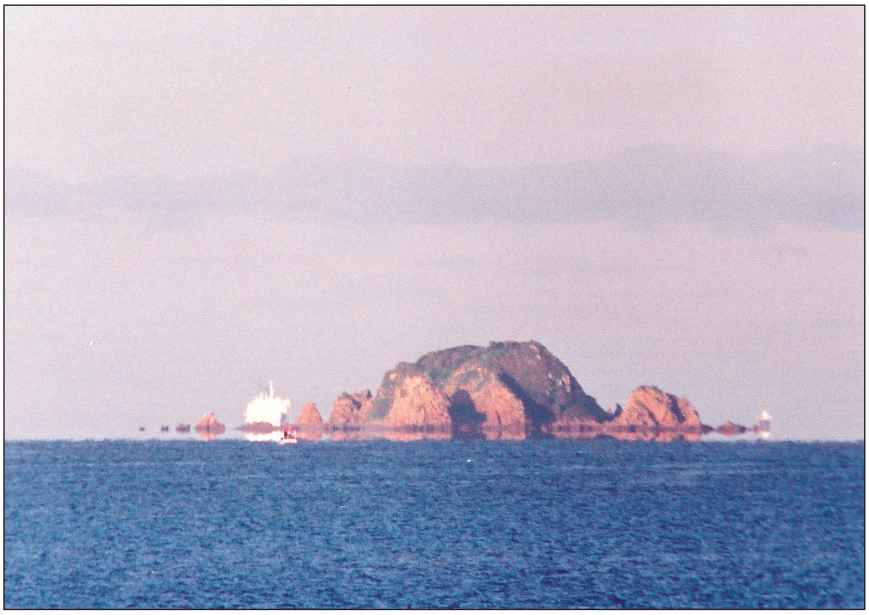

PLATE 5.3. The mirage produced by a cool katabatic wind flowing from the Hutt Valley across the warmer water of Wellington Harbour. (W. Ireland).

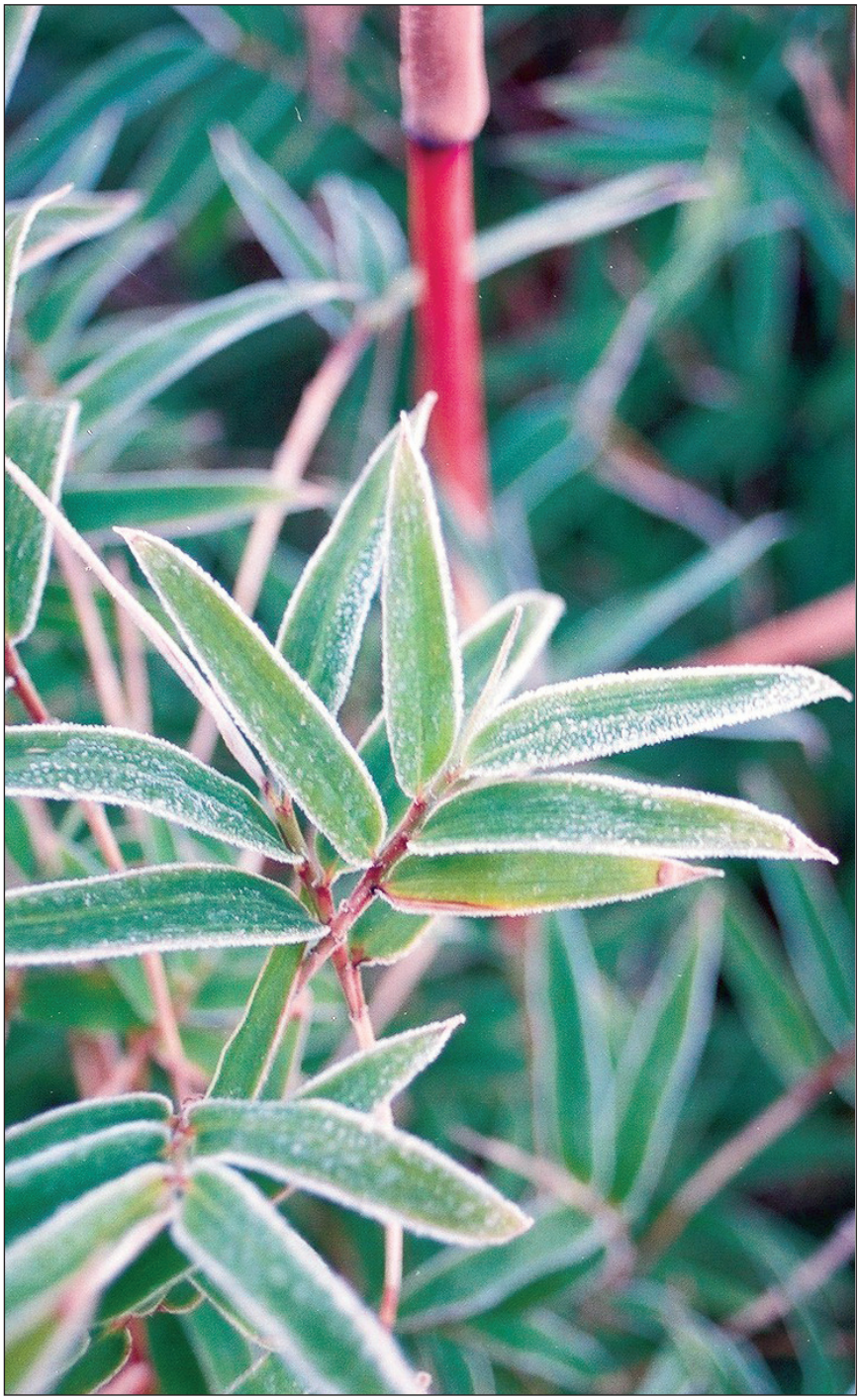

PLATE 6.1. Photograph showing most hoar frost at the edges of leaves, although the centres of the leaves are colder than the edges. (W. Ireland).

PLATE 9.1. Photograph showing the frost protection afforded by a fence in a radiation frost. Close to the fence the lawn is covered with dew, further away the dew has turned to frost. (W. Ireland).

PLATE 11.1. Photograph showing an orchard after a night when targeted sprinklers were used for frost protection at Earnscleugh. (Lincoln Ventures Ltd).

PLATE 11.2. Photograph showing a line of targeted sprinklers after several hours operation in a radiation frost at Earnscleugh. (Lincoln Ventures Ltd).

PLATE 11.3. Photograph showing a tree that received insufficient water overnight when sprinklers were used for frost protection at Earnscleugh. There are no visible icicles and the ice is white. (Lincoln Ventures Ltd).

PLATE 11.4. Photograph showing a tree that received too much water overnight when sprinklers were used for frost protection at Earnscleugh. There are large icicles and a branch broke under the ice load. (Lincoln Ventures Ltd).

PLATE 11.5. Photograph showing icicles on a tree that received adequate water when sprinklers were used for frost protection at Earnscleugh. The icicles are clear and glassy. (Lincoln Ventures Ltd).

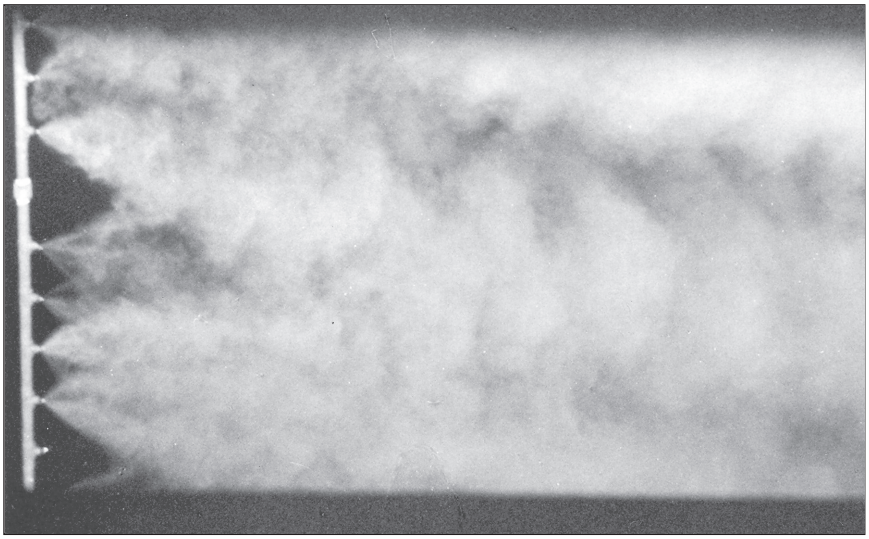

PLATE 12.1. Photograph showing fog issuing from a line of 'Mee' fog nozzles in a radiation frost at Roxburgh. (W. Ireland).

PLATE 12.2. Photograph showing the fog from a line of 'Mee' fog nozzles falling about 8m to the ground, landing close to the line in calm air, in a radiation frost at Roxburgh. (W. Ireland).

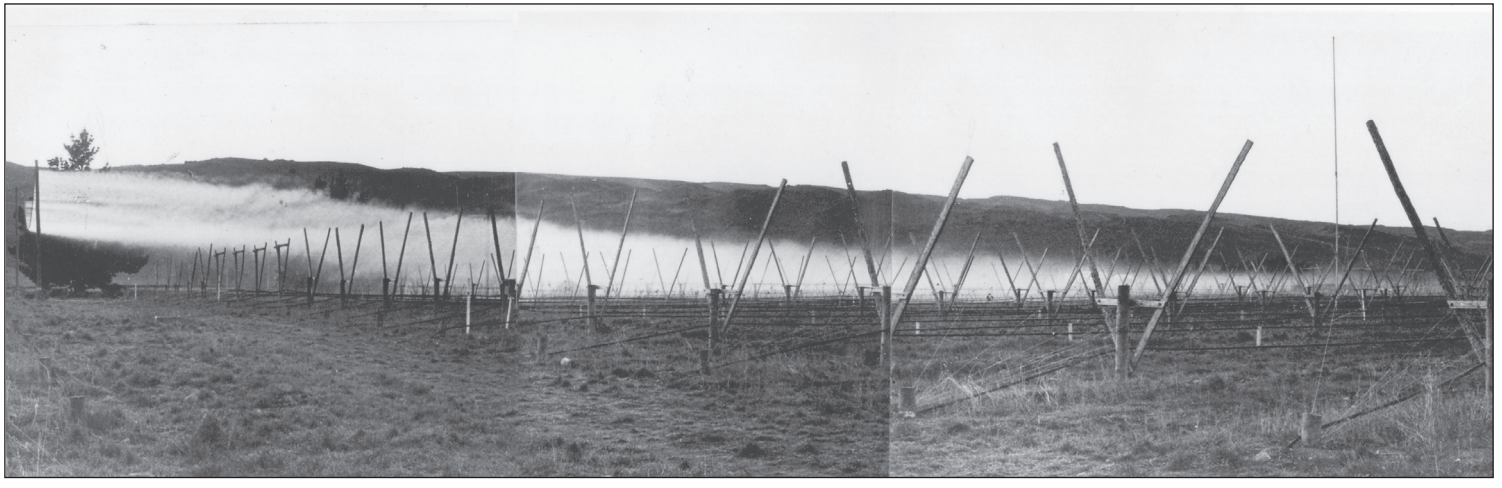

PLATE 12.3. Photograph showing fog streaming from a line of 'Mee' fog nozzles about 8m above the ground, none landing less than 50m from the line in low wind, and some travelling at least 300m, in a radiation frost at Roxburgh. (W. Ireland).

PLATE 13.1. Photograph of a ducted horizontal-axis fan in a vineyard in the Napa Valley. (W. Ireland).

PLATE 13.2. Photograph of a near-horizontal-axis two-bladed propeller wind machine in a vineyard in Marlborough. (W. Ireland).

PLATE 13.3. Photograph of a pair of near-horizontal-axis four-bladed propeller wind machines in a vineyard in Martinborough. (W. Ireland).

CHAPTER NINE

MODIFIED ENVIRONMENT FROST CONTROL

INTRODUCTION

No special action is required when a frost occurs if the frost climate has been either temporarily or permanently modified by a suitable technique. Anything that affects the radiation from the surface or the heat transfer between the ground and the air near the ground will affect frost severity, so control of radiation from the surface can be used for 'passive' frost control. An opaque cover reduces the radiant heat loss from a crop with the result that the crop temperature more closely approaches the temperature of the surrounding air. Individual plant covers, louvred shades, Dutch light frames, cloches, plastic covers, greenhouses, orangeries, nearby walls and fences have all been used to reduce radiant heat loss. The higher temperature below and beside such structures may bring the plants to maturity earlier than plants grown in the open in addition to providing effective frost protection. Frost risk can be reduced in some cases by soil banks or raised fields surrounded by water and by selecting orchard sites on shaded slopes or behind shelter for increased chilling. Cutting a break in a hedge may sometimes reduce frost risk by allowing katabatic flow to replace ponded cold air with warmer air from above. High shelter will provide some radiation shielding and act in the same way as a canopy.

BARE GROUND

A compacted or wet soil will generally reduce frost severity relative to that over a loose dry tilth but irrigation can increase frost risk if it is followed by extensive evaporation during the day.

Several experiments have shown the effect of small areas of bare ground in otherwise extended grassed areas. Close to the surface a significant increase in air and plant temperature is noted but the height to which a useful effect is observed depends upon the area of bare soil.

Figure 9.1 shows the distribution of minimum temperatures over an 8m by 12m bare soil surface at the Voeikovo Meteorological Station, Ukraine USSR (Romanova & Kaulin 1960). Unshielded minimum thermometers were placed in the soil surface and 20, 50, 100 and 200mm above ground. The temperature 2m above ground was read from a minimum thermometer in a meteorological screen. On clear nights with frosts and wind speed 500mm above the ground less than 1m/s a minimum thermometer 50mm above the surface was 1.5 to 2.0˚C below surface temperature and sometimes exceeded 4˚C cooler. On clear nights with wind speed greater than 1m/s at 500mm the minimum indicated temperature was 20mm above the surface and 1.5˚C cooler than the surface. With overcast and cloudy skies wind speed was about 3 to 5m/s and the minimum temperature was indicated either at the surface or 20mm above.

A comprehensive series of measurements was made during summer frosts in 1991 in a sub-alpine forest area that had been clear-cut in 1981 near Kamloops, B.C. Canada (Adams & Black 1994). The ground cover was predominantly grass and herbs 150 to 300mm high and four small areas were cleared of all organic material to leave bare soil. Minimum air temperatures 150mm above a 6m x 6m square plot were 2 to 3˚C warmer than those at the same height in the grass canopy. There was no warming in the air in either a 1m x 5m strip

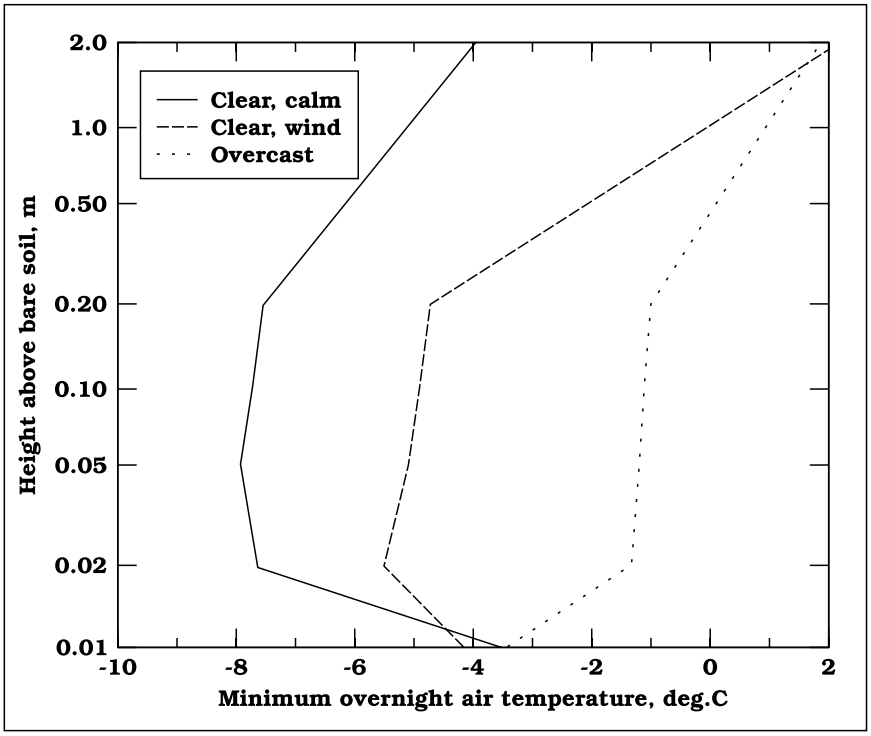

FIGURE 9.1. Distribution of overnight minimum air temperatures over an 8m by 12m bare soil surface. (After Romanova & Kaulin).

nor in a 500mm x 5m long vee trench 300mm deep. Minimum air temperatures in a 1m x 5m long vee trench 300mm deep were approximately 1˚C warmer than in the grass canopy. When wind speed was low on clear nights the surface temperature of the bare soil in all plots was 5 to 7˚C warmer than the apparent surface temperature of the grass. When the wind speed exceeded 400mm/s at a height of 150mm above the centre of the plots (above the nadir of the trenches) the bare ground surface temperatures were within 1˚C of the grass surface temperature. The temperature of 1mm diameter ceramic and 5mm and 10mm diameter nylon cylinders 150mm above the surface was measured to simulate the temperature that would be experienced by conifer seedling shoots during summer frosts. The 1mm cylinders were less than 1˚C cooler than the ambient air. The larger cylinders were only 0.5˚C cooler than the ambient air above the 6m by 6m plot and the wide trench and up to 2˚C cooler than the ambient air above the grass surface. It was concluded that the shoots of seedlings growing in the one metre wide trenches were up to 2˚C warmer than those growing in the grass canopy.

The effect of very small plots of bare soil on the frost temperature of Eucalyptus leaves at several heights above ground was studied in Canberra, Australia in Winter 1984. Two 1.2m x 1.2m square plots of bare soil were established in a meteorological enclosure. One plot was kept dry, the other moist. The grass surrounding the plots was dense and about 25mm high. Figure 9.2 (Leuning and Cremer 1988) shows overnight temperature of small

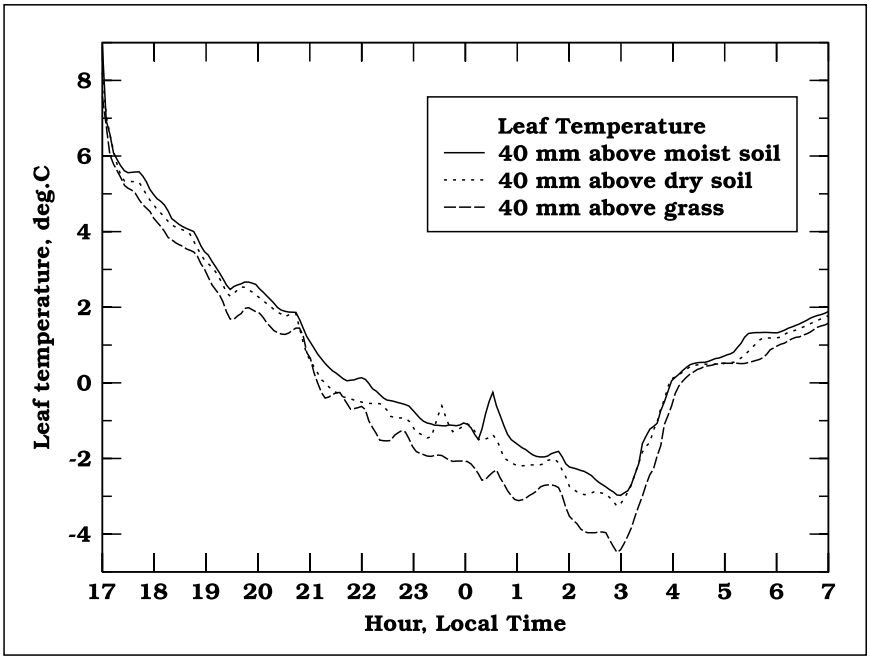

FIGURE 9.2. Temperature of small Eucalyptus leaves 40mm above 25mm-tall grass, dry soil and moist soil in a radiation frost, showing the effect of the underlying surface. (After Leuning and Cremer).

leaves 40mm above grass, above dry soil and above wet soil. Leaf temperature on clear nights was lowest above the grass, intermediate above the dry soil and highest above the moist soil. The maximum difference was about 1°C.

GRASS COVER

An insulating layer such as a thick grass sward will increase the severity of frost above the layer but may or may not reduce it below. The cooling effect of long grass will have greatest effect on low-growing crops but may well be negligible for fruit two metres or more above ground.

As a general rule the upper surface of an insulating layer such as grass will be cooler in a radiation frost than the surface of bare ground. Vegetation screens the soil from the sky and raises the effective radiating surface above the ground with consequent modification of the air temperature and wind speed profiles on clear nights. The effective radiating surface of soil covered with uniform vegetation such as grass will then be at some intermediate position near the top of the layer of grass. The grass and air within the layer restrict heat flow from the ground to the radiating surface because the conductivity of the insulating layer is lower than that of the soil below. The grass surface will cool further than bare ground and the earth surface below the grass will be warmer than bare ground. An insulating layer affects overnight air temperature only up to a height that is controlled by the insulating properties and area of the layer and the wind speed. The effect of a few square metres of insulating cover surrounded by a large area of bare ground will not extend above about one metre.

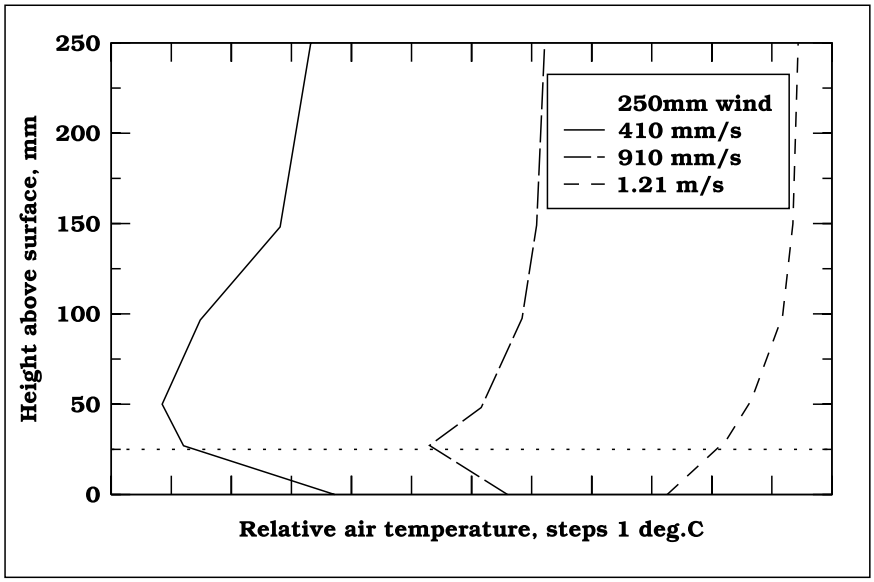

FIGURE 9.3. Air temperature profiles observed over an extensive area of regularly mown short grass at Hamilton on clear calm nights. The dotted line at 25 mm indicates the top of the grass. (After Oke).

Figure 9.3 shows three air-temperature profiles found close to the surface of an extensive area of short grass (25mm high) on a clear night at Hamilton, Ontario Canada (Oke 1970). When the wind speed 250mm above the ground was less than 400mm/s the coldest place was 25 to 75mm above the grass (50 to 100mm above ground). The grass tips were the coldest place when the wind speed was about 700mm/s; they were 4˚C colder than the soil surface. When the wind exceeded 1.1m/s the coldest place was at the soil surface.

A sequence of air temperatures measured under a clear sky overnight in a rice paddy field at Hachihama, Japan shows that the minimum temperature near the tops of the plants 0.75m above ground could be at least 3˚C colder than the air at the surface, as shown in Figure 9.4 (Maitani et al 1984). There were 25 to 30 plants per square metre, about 0.75m tall with a leaf area index of 3.6.

ORCHARD SURFACE COVER

On occasion improved plant growth in an orchard may be a more important result than any significant improvement in frost tolerance of a crop growing above a grass cover crop. Allowing grass to grow long in winter or cultivating the soil to a loose tilth can cool an orchard and increase the chilling of the crop with improved bud burst and better fruit set later in the year. When spring arrives the grass cover is removed or cut very short, or the soil is rolled and compacted. It would seem to be important to wait until bud movement is first observed before shortening the grass in spring to ensure that bud break is delayed as long as possible and make late frost damage less likely.

Investigations by the United States Weather Bureau have shown that orchards with heavy cover crops are on average colder by 0.3˚C at a height of 1.5 metres and 0.7˚C at a height of 250mm above ground than clean-cultivated orchards. It has also been suggested

however that 'The presence of cover crops in mature deciduous orchards probably has little or no effect on the frost hazard, since the lower branches of the trees usually are several feet above the ground' (Young 1947).

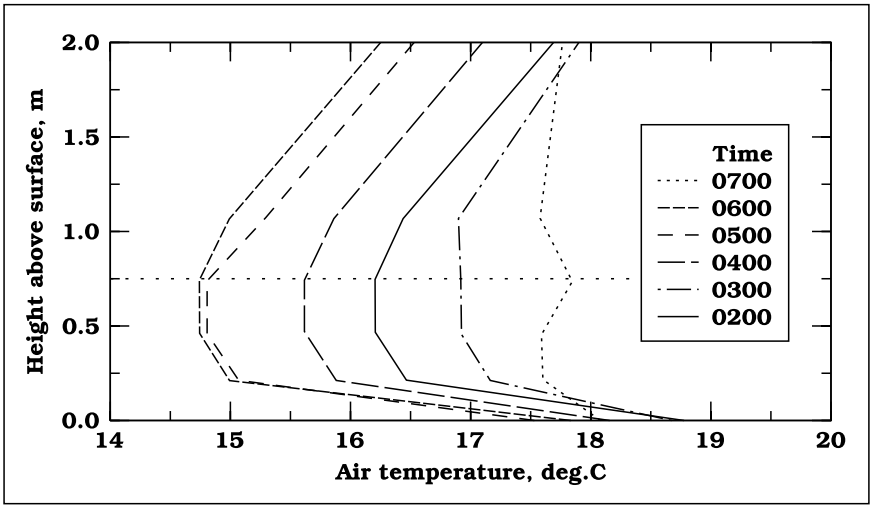

FIGURE 9.4. Air temperature profiles at specified local times on a clear night, over a rice paddy field at Hachihama. The dotted line at 0.75 m indicates the tops of the plants. (After Maitani et al).

ORCHARD CANOPIES

The relative areas of tree canopies and the open spaces separating the trees will determine the effect of orchard canopies. The effectiveness of tree canopies as radiation screens increases with leaf area. The leaves will also impede air movement through the canopies. As a result the position of the coldest temperature reached by a canopy crop during a frost can move from near ground level to near the top of the vegetation as leaf area increases. On the other hand the surface below heavily foliated canopies may be warmer at night than flat cultivated surfaces nearby. Apple trees in full leaf are sometimes frosted at the top in spring with little damage lower down. The upper leaves of Kiwifruit growing on horizontal trellises may be frosted in autumn, leaving the fruit below undamaged. Trees devoid of leaves are damaged first at lower levels. Trunk damage to young Kiwifruit vines in winter typically occurs 100 to 150mm above the ground.

Typical wind speed profiles for frosty nights in an orange orchard at Riverside, California USA in winter 1938-39 are shown in Figure 9.5 and the corresponding air temperature profiles in Figure 9.6 (Kepner et al 1942). The trees were about 3.4m high with 3.4m diameters and spaced 6.1 by 7.3m apart. Minimum air temperature was typically found between 0.9 and 1.4m above ground.

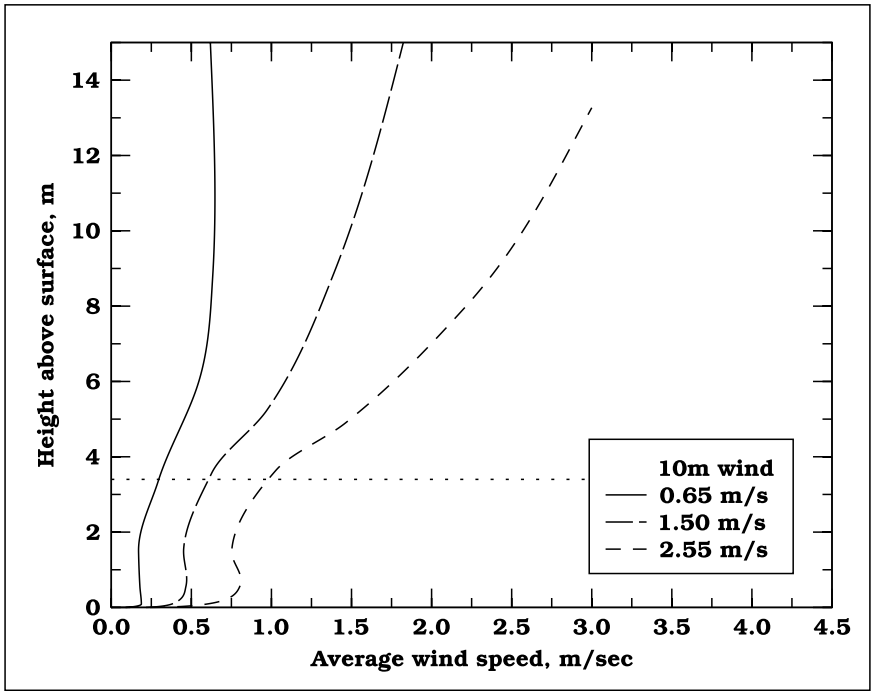

FIGURE 9.5. Typical wind speed profiles observed in and above an orange orchard on clear relatively calm nights at Riverside. The dotted line at 3.4 m indicates the top of the trees. (After Kepner et al).

SHELTER

The climate of sheltered plots as the shelter trees grew was studied during the establishment of the Horticultural Station at Kerikeri, New Zealand from 1980 (McAneny et al 1990). In six years the station went from bare fields to a network of 0.5ha blocks separated by natural shelter trees up to 10m high. The trees used for shelter were Cryptomeria, Casuarina, bamboo and Eucalyptus. Daytime maximum air temperatures and soil temperatures increased about 0.1˚C/m of shelter height compared with reference meteorological data taken outside the sheltered area. Minimum air temperatures within the sheltered area showed a tendency to be lower but no consistent relationship was found with shelter height. This suggested that for a 10˚C base temperature an additional 200 degree-days would accrue for a crop protected by 10m-high shelter.

The design of shelter for horticulture is not simple. What may appear to be good shelter may result in gustiness if it is not sufficiently permeable and may cause unacceptable rub damage to ripening fruit. The requirements for shelter and frost protection may be different. Windbreaks and shelter are generally believed to increase the severity of frosts when they reduce the mixing of the air near the surface. Since it is the air nearest to the ground that should be allowed to flow freely during a frost shelter trees should be cleared of branches up to say 2m above ground. This may or may not affect their efficiency as shelter trees for wind protection. Allowing cold air to flow may increase nighttime orchard temperature because the moving air is able to transfer heat from higher levels to lower levels more effectively

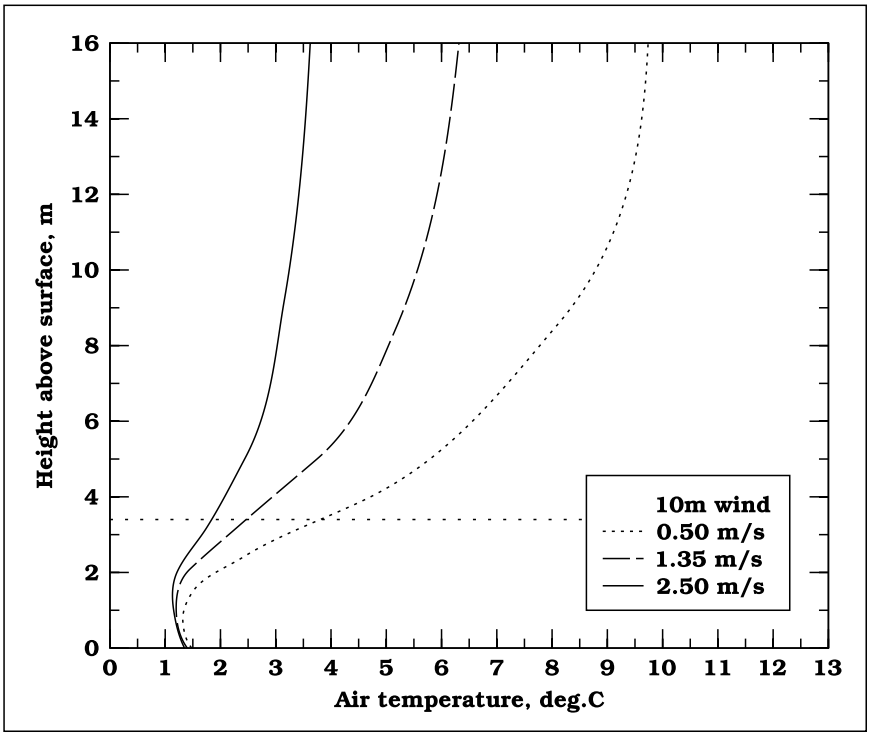

FIGURE 9.6. Typical air temperature profiles observed in and above an orange orchard on clear relatively-calm nights at Riverside. The dotted line at 3.4 m indicates the top of the trees. (After Kepner et al).

than still air. It appears that air drainage on slopes should not be impeded by shelterbelts; ponding and reduced airflow may result in lower temperatures that increase frost damage.

The air temperature in an orchard of heavily-foliated trees such as Citrus may easily be a few degrees cooler at night than in an open field well away from shelter. Figure 9.7 (Brooks et al 1962) shows the average hourly temperatures on fifteen frosty nights in winter 1950-51 at Riverside, California USA. At a height of 1.5m the air inside a Citrus orchard was as much as 3°C cooler than in an open field yet the temperature 12m above ground was the same in both places. A given low air temperature is reached four to six hours earlier in the orchard than outside.

MODIFICATION OF SURFACE EMISSIVITY

Coal dust has been applied to the surface of bare soil in a series of frost control experiments in West Virginia, USA (Sharratt & Glenn 1986, 1988a, 1988b). In 1985 coal dust was spread evenly over three metres wide strips of the bare soil surface in a 1.4 hectare peach orchard. Approximately 18.1 tonnes per hectare (18.1Mg/ha) of coal dust mixed with 1Mg/ha of fibre mulch was used. Grass-covered strips 3m wide alternated with the coal-covered strips. A similar 1.4ha peach orchard alongside was used as a control. The control orchard had alternating grass and bare ground strips. In 1986 the control orchard was fully grassed and

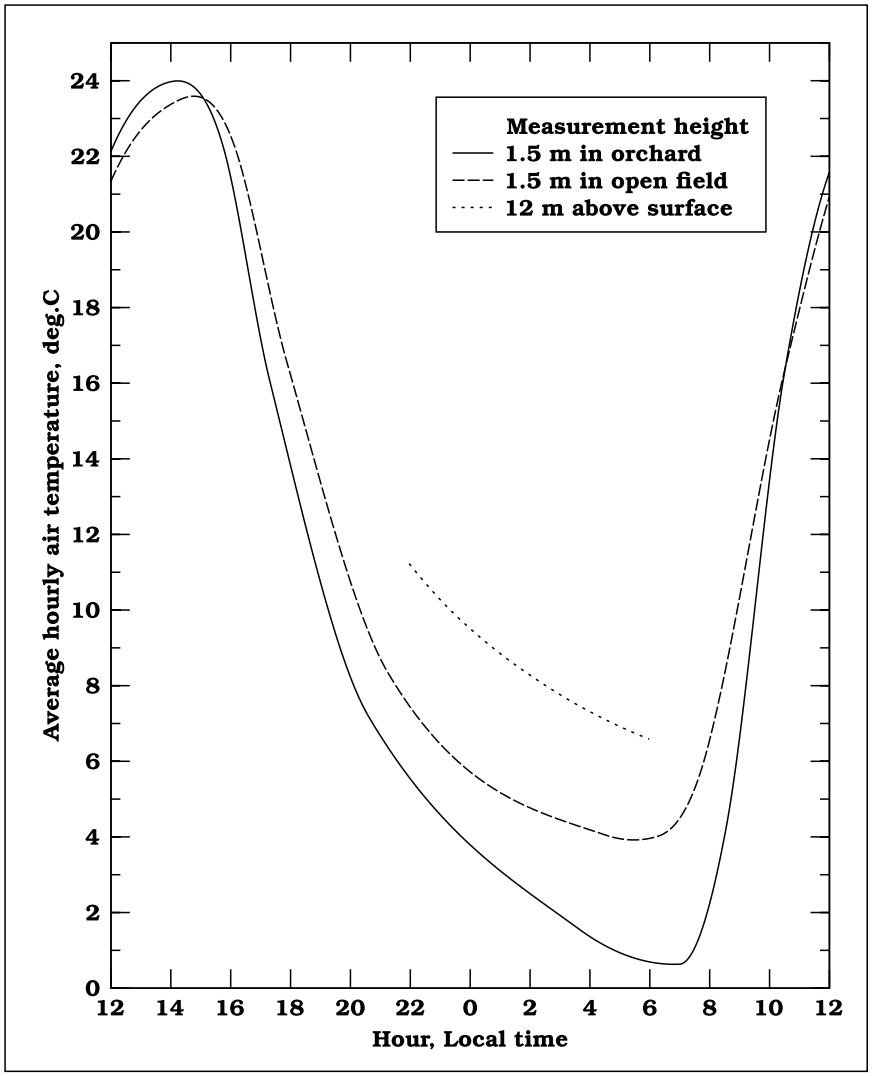

FIGURE 9.7. Smoothed averages of hourly air temperature recorded inside and outside a heavily-foliated Citrus orchard at Riverside, on fifteen clear nights in winter 1950-51. (After Brooks et al).

the layer used to control soil emissivity in the experimental orchard was thickened to 2 to 5mm using 44.8Mg/ha of coal dust.

The coal dust covering caused more solar energy to be absorbed and retained by the ground than was taken up by the grass-covered plot. As a result daily average soil temperatures 10 to 50mm below the coal dust during spring were about 2.5˚C higher than below grass. Daily average air temperatures were generally about 0.2˚C warmer in the orchard treated with coal dust. Air temperature at canopy height (1-2m) on frosty nights was cooler by 0.5˚C in 1985 and warmer by 0.5 to 1.5˚C in 1986 in the coal dust plot. The temperature of

buds 1.5m above ground showed little response to the modification of surface emissivity by application of coal dust.

It appeared that little of the heat radiated from the soil at night was intercepted by the canopy. Bud temperatures in the experimental orchard were between 0 and 0.5˚C warmer than in the control depending upon wind speed. At 2m/s wind speed the bud temperatures differed by less than 0.2˚C between plots, at 1.3m/s the buds in the treated plot were about 0.5˚C warmer than the controls.

INSULATING FOAMS

Extensive research has shown that insulating foams can give up to 10˚C protection to low-growing crops from a few hours to well over a day. The technique has not been widely applied and little work has gone into developing suitable foams and foam generators (Bartholic & Braud 1979).

A foam blanket from 100 to 200 millimetres thick is typically sprayed from a tractor-mounted foam generator on to a low-growing crop such as strawberries. It is applied as late as possible in the afternoon when a damaging overnight frost is expected. The foam gradually disintegrates but is designed to provide up to 10˚C frost protection for several hours. Foam remaining 24 hours after production is unlikely to be effective the second night.

The minimum temperature of the soil surface underneath foam covering of the order of 100 to 200mm depth can be up to 12˚C warmer than an unprotected surface. Inside the foam the temperature excess decreases with height and the upper surface will be of the order of 2˚C colder than the air at the same height. Low-growing plants can be kept about 2 to 3˚C warmer than unprotected plants during a frost.

There are numerous non-toxic foaming agents available and foam generators may be built inexpensively. A suitable foam will be composed of a foaming agent such as a synthetic detergent, a film stabilising agent such as gelatine, Citrus pectins and starch phosphate and if necessary a moisture binding agent or a drainage retarding agent. The foams used for fire fighting lack the stability required for frost protection. Thermal conductivity of useful foam is of the order of 0.11W/m˚C. Stability is satisfactory for an expansion in the range 15 to 80. Wind destroys highly expanded foam.

A Canadian paper describes conditions inside a protein-based foam used to protect small plants from frost (Desjardins & Siminovitch 1968). The foam consisted of a 3% solution of a stabilised concentrate of hydrolysed protein in water containing 1% gelatine. Because of its high density this foam had to be spread all around the small plants to support them. A plot 1.2 by 1.2 metre was covered with a layer of foam 170mm deep at 5pm. Temperatures were measured regularly at several heights above, within and below the foam.

The foam very effectively prevented overnight heat loss from the ground. The minimum temperature of the ground surface was kept about 3˚C higher below the foam than it was below the grass of a control plot. Inside the foam the minimum air temperature was between 3 and 6˚C warmer than outside at ground level, falling to equal to outside air temperature at a height of the order of 100mm, then falling below air temperature by upwards of 2˚C up to the top surface of the foam. The maximum temperature gradient inside the foam was about -58˚C/m at overnight minimum. This experiment suggests that the particular foam used would need to extend a few centimetres above the top of the plant material to protect it from frost damage.

The quantity of foam required may be gauged by the results of a test in East Germany where the protein-based foam ‘Neomerpin SPR-15’ was found to be stable over 16 hours at temperatures below 0˚C (Hort. Abstr. 1987). Using tractor-operated equipment 2-3 people

covered one hectare with 1,250 litres of protein foam builder and 23,750 litres of water. A 200mm thick layer protected strawberry, tomato and potato plants from 8 hours of frost (-8 to -10˚C). It did not affect flowering, pollination or fruit set. The foam could not be applied in a wind exceeding 1m/s or in rain.

Air temperature at leaf height, 25mm above the trench bottom and soil temperature 25mm below the surface increased by about 7˚C and 2˚C respectively when foam was applied in shallow trenches late on a frosty evening and by morning were about 12˚C and 8C warmer than control temperatures. The results of this test are shown in Figure 9.8 (Heilman et al 1970).

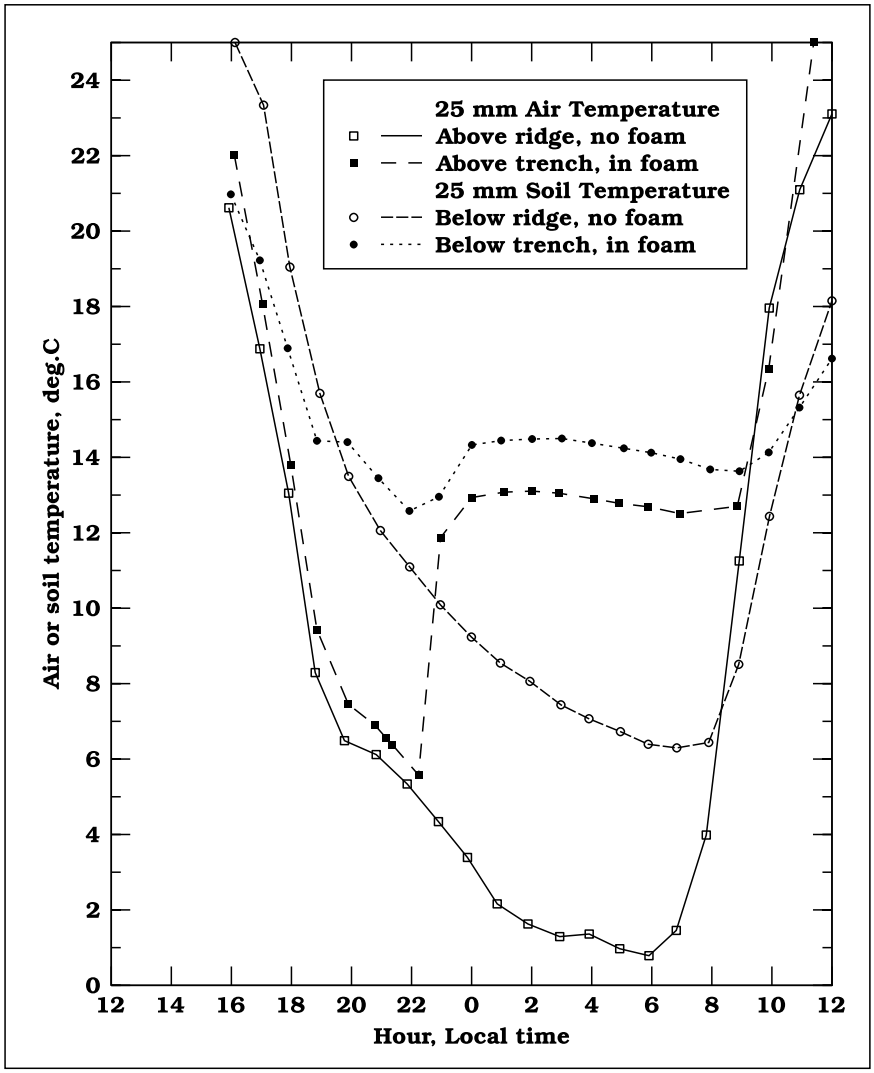

FIGURE 9.8. The effect of a water-based foam on the air temperature 25mm above ground, and the soil temperature 25mm below the surface, on a clear night. The foam was applied at 2230 hours. (After Heilman et al).

ORGANIC MULCHES

Organic mulch layers such as straw or sphagnum moss may remain in place all season and have the same insulating effect as grass or other vegetation. Mulch reduces the amount of heat entering the soil during the day so the average soil temperature under an extended mulched area will be lower than it is over bare ground. The better the insulation the colder the top surface of the mulch and the air become overnight. The overnight temperature within the mulch will be intermediate between that of the top surface (coldest) and the ground (warmest).

The temperature of the air above mulched ground was studied in a peach orchard in Australia (Jenkins 1968). Minimum temperature on one frosty night was -2˚C on the top surface of a straw mulch when the minimum temperature on top of bare oil-sprayed ground was 3˚C. The minimum temperature over a clover sward and the loose surface of freshly cultivated soil was intermediate between that over straw mulch and bare soil. On another night, in a large block of apricot trees, shielded minimum thermometers at a height of 1.2m registered -2.2˚C over the half of the block that was mulched and 0.6˚C over the other half that was non-mulched, weed-free, slightly-compacted and cultivated.

For frost protection of low-growing plants it appears to be necessary to restrict the area of mulch to the minimum amount to just cover the plants to be protected. Then the average soil temperature below the mulch will remain almost as high as in areas with clear ground. Overnight temperature of the plants within the mulch may then be expected to be higher than if they were exposed.

The increased frost risk above organic mulches differs from the reported success of straw mulch in preventing winter damage to strawberries in the USA (Hort. Abstr. 1986, 7642). The crowns of plants on straw-mulched beds were warmer in winter than those on non-mulched beds. The crowns of plants grown on raised beds were colder in winter than those on flat beds. Severe winter injury occurred on raised beds without mulch even when covered with 100mm of snow.

PLASTIC FILM MULCHES

The effect of a single thin layer of impermeable polythene mulch depends upon its colour (Parker & Baird 1979). The average daily temperature 50mm below the surface of soil covered with black polythene is about the same as that of bare soil. The maximum and minimum soil temperatures however are less extreme under the black plastic and they lag the open soil temperatures by about two hours.

Clear plastic mulch increases the average soil temperature at 50 to 200mm depth by several degrees; up to 12˚C has been recorded. The clear plastic film increases the solar energy stored in the soil by day and the rate of heat loss at night is reduced so more heat is available later in the night to combat frost. Clear plastic mulch therefore keeps the ground several degrees warmer than opaque black plastic mulch.

The effects on overnight air temperature and hence leaf or bud temperature for crops grown over plastic mulches do not appear to have been reported.

SOIL BANKING

Small Citrus trees are sometimes protected from trunk damage in winter by banking up soil to above the bud union (Young 1947). Temperatures around the trunks of soil-banked Citrus may be 4.4 to 6.7˚C higher than for unprotected trees (Hort. Abstr. 1985). A severe frost

may kill all the growth above the soil bank but a new top can grow faster than a new tree. Disadvantages of the soil banks for Citrus include annual construction and removal costs, disease and injury hazard. For potatoes however moulding-up around newly emergent vegetation the day before a severe frost occurs is an effective protective measure.

RAISED FIELDS

Before the Spanish arrived in South America more than 82,000ha of raised fields were used for agriculture in the Lake Titicaca region of Bolivia and Peru (de Lozada et al 1998). Raised platforms up to 1.2m high and 2 to 20m wide are surrounded by water-filled canals 1.6 to 4.5m wide. The effectiveness of the technique in reducing potato crop damage by mid-season frosts has been investigated. On frosty nights minimum air temperatures 0.5m above the raised platforms were about 1˚C higher than on flat fields nearby. The differences in air temperature were consistent with natural convection and cold air drainage back to the canals.

TRUNK WRAPPINGS

Trunk wrappings are commonly used to protect young Citrus trees from freezing injury (Fucik 1979). Permanent wraps of insulating material are bound tightly around the trunk for 3 to 4 years. Bud unions must be no less than 150mm above ground to overcome foot rot (Phythopthora parasitica) and the trunk should be treated with a fungicide-insecticide spray before fitting the wrap. The wrap is made so thick that the rate of temperature change under the wrap is about half that of the rate of change in air temperature. As a result the temperature decrease under the wrap lags behind the air temperature and the time for which the trunk is exposed to freezing temperature is reduced. If air temperature stays low for a long time the trunk will eventually reach much the same temperature as the air and the trunk will be damaged.

Various wrappings have been used in the past. Corn stalks, mineral wool encased in roofing felt, fibreglass batts wrapped in chicken wire and aluminium foil on corrugated cardboard have been used with varying effectiveness. The most commonly used wrappings for Citrus trees in the USA in 1977 were snap-on closed-cell polystyrene and expanded polyurethane foam batts. The polyurethane foam trunk wrap is about 380mm high and 90mm thick. It is made by rolling a 30mm x 380mm x 1070mm batt around the trunk and securing it by aluminium bands. The cost of installing polyurethane wrappings was about 75 cents US per tree in 1977 and 15 cents to remove them 3 to 4 years later. Both of the synthetic wrappings provide less protection than the traditional soil banks. In one test the near-trunk temperature under wrappings was only about 1.5˚C warmer than for unprotected trunks compared with 4.4 to 6.7˚C warmer under soil; in another test the temperature under wraps was -2˚C when air temperature was -6˚C (Hort. Abstr. 1985).

Trunks of young Kiwifruit vines (1 to 3y old) may be damaged by early winter frosts. Splitting on the sunny side of the trunk and ring barking may occur about 100 to 150mm above the ground. Insulating trunk wraps have been used successfully in a field experiment at Riwaka, New Zealand (Pyke et al 1988). Various methods of lagging the trunks of young vines from ground level to 300mm have been evaluated. Temperature was measured on the bark surface 150mm above ground level. The daily minimum temperature during frosts was always warmer below wraps than on bare trunks. The sawdust mound gave up to 4.4˚C protection, hay and polythene up to 3.2˚C and the other wraps at least 0.4˚C. Daily maximum bark temperature depended on the wrapping used; sawdust kept the surface as much as

7.1˚C cooler while black paper made it as much as 6.7˚C higher than control trunks. The wrappings always delayed the changes of bark temperature, the greatest delay and the least diurnal range occurring below the sawdust. The effectiveness of the various trunk wrappings is illustrated in Figure 9.9 (Pyke et al 1988). Most effective was a sawdust mound 20mm thick at the top. Hay 50mm thick surrounded by a black 0.5mm thick polythene wrap was next, equal in performance to a 50mm thick polyurethane foam insulator.

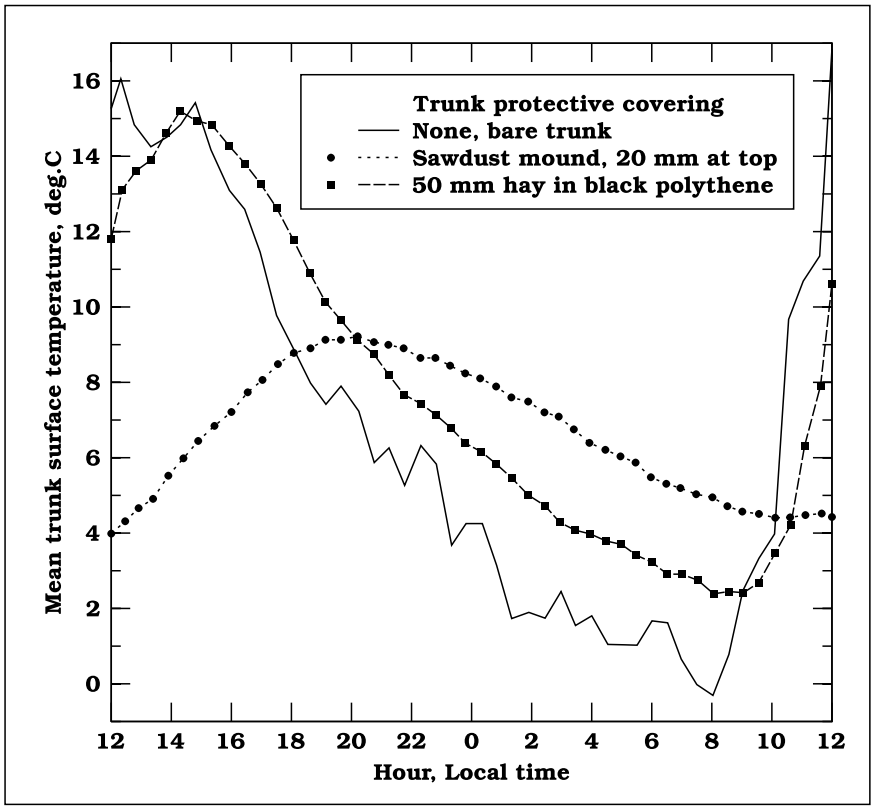

FIGURE 9.9. Effect of protective wraps on the surface temperature of Kiwifruit trunks during two days when frosts occurred at Riwaka. The wraps were 300 mm high and the temperatures were measured 150 mm above ground on the southern side of the trunks. (After Pyke et al).

MODIFICATION OF TRUNK EMISSIVITY

Painting the trunks of deciduous fruit trees white can reduce winter damage (Hellmuth et al 1988). The surprising feature of this method is that the cambium on the sunny side of a white-painted trunk can be kept 8 to 16˚C cooler on a winter day than that on an unpainted trunk. As a result the painted trunk hardens more than the unpainted and can withstand more severe frosts. Desirable paints should be easy to apply, be durable, not flake off and not injure the tree. There is some disagreement over which paints cause tree damage; good quality indoor white latex paint appears to be the most satisfactory for preventing winter sun scald injury.

MODIFICATION OF LEAF EMISSIVITY

Aluminium powder has been applied to the upper leaves of individual grapefruit trees as a means of reducing radiative heat loss. Emissivity was reduced from about 0.92 to 0.80 by the powder and net radiation loss above treated trees was reduced by as much as nine per cent. Leaf temperatures were 0.6 to 0.9˚C higher overnight in the treated trees compared with the leaf temperatures of untreated trees surrounding them. Silicone oil coating had no effect and a carnauba wax coating actually decreased leaf temperatures by 0.3˚C relative to untreated trees (Hales 1974).

INDIVIDUAL PLANT COVERS

Low-growing crops can be 'forced' by 'brushing', covering individual plants partially or wholly with brushwood and burlap or paper. The coverings are generally in the form of a 'tepee' open on the sunny side (Young 1947). Daytime temperatures can be from 5 to 13˚C warmer under the covers than in the open. Overnight minimum air temperatures are typically 1˚C warmer under the covers. The plants would be somewhat more than 1˚C warmer than plants in the open.

Citrus trees covered by heavy waterproof paper bags during winter have been more readily damaged by frost than trees in the open (Young 1947). This apparently anomalous result is due to the loss of hardiness induced by the higher day temperatures under the bags. Maximum temperatures 1.5m above ground were 9˚C higher and 2m above ground 13˚C higher under the bags.

The technique of covering individual plants with brushwood can be extended to row crops grown on ridges. The ridges, about 0.5m high and 1.6m apart, run East-West, with the plants located about halfway up the sunny side of each ridge. Wires running the length of each row support a sloping 'roof' of brushwood and paper. Each roof is about 1m high and slopes towards the sun at about 45 degrees elevation, with its lower edge on the summit of the ridge (Bush 1947). Winter vegetables have been protected by this method in the Imperial Valley, California USA (Young 1947). Additionally, each plant may have a translucent paper cap supported on a wire arch. Maximum daytime temperatures 15˚C higher and minimum overnight temperatures 1.4˚C higher than in the open at the same level have been recorded. Crops protected were early watermelon, cantaloupe, squash and cucumber.

'Tin cans' or other metal coverings should never be used for frost protection as they are good conductors of heat and will closely follow air temperature.

SHADING SCREENS

The frost protection offered by various polythene plastic shading screens with open weave, stretched horizontally about 2.5m above an area of a quarter hectare, was evaluated in the Arava region of southern Israel in two successive winters (Teitel et al 1996). Of the several screens tested, the two that were most effective were described as '50% black' and '50% aluminised' on the basis of the percentage shading of visible light measured below samples of the screen materials illuminated from above. They were made by weaving strips of black polythene and by weaving strips of clear polythene film that had a thin layer (0.2um) of aluminium respectively. The temperature of the upper leaves of a crop of Capsicum about 700mm high, air temperature 400mm above ground and ground temperature 50mm below the surface were recorded. Ground and air temperatures at night were approximately equal

between the '50%' screens, but the upper leaves under the aluminised screen were about 0.8 to 1.0˚C warmer than those under the black screen.

A large louvered 'Venetian Blind' has been used to cover a soybean crop (Martsolf & Decker 1970). The louvers were about 300mm wide, tilt able and separated by 150mm (450mm between centres). They were mounted on a horizontal frame 1.5m above ground, covering an area 6.25m x 4.4m. The louvers were covered with heavy-duty aluminium foil on both upper and lower surfaces. Temperature below the louvers was warmer at night and cooler during the day than in the open. Leaf temperature was measured somewhere between ground and 1m and at about 6am was found to be some 2.5˚C warmer below the screen than outside. Daytime leaf temperature maxima were about 2.5˚C lower than for unshaded leaves.

Screens that are impervious to light would need to be removed during daytime to allow the ground to warm up. Such screens would be practical only if needed very rarely, could easily be erected in the afternoon and could be removed the next morning as required. They would increase overnight air temperature by perhaps 1 to 3˚C and crop temperature slightly more.

ORANGERIES

The Orangery built at the Palace of Versailles, Paris, France in 1685 houses 1,200 orange trees and several other plants over the winter. It has a solid opaque roof but the south-facing wall has many windows. When the danger of frost is past the trees, each in its own tub, are placed outside for the summer.

GREENHOUSES

Glass is impervious to infrared radiation so a glass greenhouse acts as an effective long wave radiation screen, preventing the heat radiated from the surface and the crops being lost directly to space. The upper surface of the glass radiates directly to space however, cooling the glass and allowing it to absorb some of the heat radiated from below. The glass also absorbs heat by convection from the air inside the greenhouse. The glass may be warmer or cooler than the surrounding external air, depending on the wind speed. The net result is that the temperature inside the greenhouse is warmer during a frost than it would be in the open. The ground surface in a greenhouse is likely to be the warmest place during a frost, the glass the coolest.

When maximum sunlight is required in a greenhouse the orientation of the long axis should be East-West. Winter sunlight is most efficiently collected if the side of the roof facing the Sun (the North side in the Southern Hemisphere) is nearly vertical.

Few definitive measurements of greenhouse temperature are to be found. Generalisations include: 'Gains in the temperature of the soil within the unheated greenhouse of up to 1.7˚C in winter and up to 5.6˚C in bright weather in summer have been measured over the comparable values outside' (Searle 1973).

LIGHT FRAMES

Tests of the efficiency of Dutch Light Frames in radiation frosts have shown that the average grass minimum temperature inside the frames was 4.8˚C higher than that outside (Hogg 1964). When water was sprayed over the frames the minimum temperature was from 7.2 to 9.3˚C warmer inside the frames than outside. The grass minimum temperature during these

tests was between -2.9 and -9.6˚C and on all occasions the temperature below the dry frame fell below 0˚C. Below the frame sprayed with water however the minimum temperature stayed between 0 and 2.1˚C.

CLOCHES

A cloche is often made of ordinary horticultural glass 3mm thick. A wire framework holds four sheets of glass together. The length and width at ground level are of the order of 600mm and the maximum height below the ridge is from 300 to 600mm. Cloches are usually arranged in double rows up to 100m long. The gap between rows is about 100mm.

The air temperature at night in spring inside cloches may be as much as 8 to 10˚C higher than outside. They provide valuable protection from spring frosts for beans, dahlias, tomatoes, melons, cucumbers, gherkins, aubergines and courgettes (Chase 1962).

Clear plastic, either rigid or in thin flexible sheet, is used extensively to form cloches and low bow-shaped tunnels much more economically than when glass is used. Extra protection from frosts can be obtained by placing matting over the tunnels.

PLASTIC COVERS

A greenhouse covered in thin PVC sheeting (about 160microns thick) will not remain as warm as a glass-covered house because the thin PVC will not be an effective radiation shield. If dew settles on the PVC however its shielding efficiency will be increased and a somewhat higher internal temperature will result (Kittas 1986).

The possibility of protecting crops from frost damage by enclosing them under a plastic screen that was covered in a light layer of ice was tested with air temperature down to -20˚C (Cary 1974). The test screen was about 4.5 by 6.5m, 1.5m high, with a complete clear plastic top and black plastic side covering. The enclosure was considered rather too small to be very effective and the gaps between the top of the plastic sides and the screen allowed a rapid exchange of outside air with that inside.

Temperature inside the screen was warmer at night and cooler during the day than in the open. It was suggested that such a screen might be helpful in preventing the loss of cold hardiness in twigs and buds on warm days during winter. Simulated twig temperatures were 2 to 10˚C warmer inside the enclosure during a variety of weather conditions.

WALLS AND FENCES

A wall facing the Sun can give considerable frost protection to a low growing plant close by, or trained up it. The wall gains heat from sunshine during the day and releases it at night, maintaining a higher temperature close by than would otherwise exist. At night a wall may cool more slowly than the ground because radiation towards the sky is less from a vertical wall than from a horizontal surface. Radiation from the ground near the wall is also less than in the open because the warmer wall partly obscures the cooler sky and the ground cools less. The sunny side of a substantial wall can provide a convenient frost-free location for sensitive low growing plants. A plant growing beside a wall may also be subject to less chilling during winter than similar plants grown away from the wall and would have an altered bud break.

The frost protection afforded by a picket fence has been seen on the surface of an adjacent lawn, as shown in Plate 9.1. Well away from the fence a layer of frost was seen on

the lawn. Closer to the fence the lawn surface was free of frost and covered only by a layer of dew. Tracks were visible where a bicycle was wheeled across the dew-covered part of the lawn. The grass surface temperature measured with a hand-held non-contact infrared radiation thermometer on a similar occasion showed the grass surface near the fence to be 1.1˚C, near the change from dew to frost, 1.5m from the fence 0.0˚C and at the left of the photo 4m from the fence -0.5˚C.

BUILDINGS

Frost near buildings and obstacles may be modified when the wind around them may be either slowed down or speeded up. Damming or stagnating katabatic flow will usually lower the air temperature and increase frost severity. Increasing the wind speed and turbulence around an obstacle will give better mixing of the air near the surface and its temperature may not fall so low as it would have been if the obstacle was absent.

CHAPTER TEN

HEATED ENVIRONMENT FROST CONTROL

INTRODUCTION

One of the oldest methods of frost fighting is to light fires throughout an orchard. Vineyards were being protected from frosts in the First Century AD by the burning of prunings and uprooted vines. Heating the surroundings as well as the crop can give effective protection to many crops. Two factors combine to protect the crop. Warm air conducts heat to the crop and the crop receives radiant heat from the heaters. The greater the proportion of heat output that is radiation, the better is the frost protection. The crop can sometimes be made warmer than the surrounding air. An important feature is that the crop and surroundings remain dry. The enormous amount of heat required to protect a crop from frost by heating the surroundings depends on the severity of the frost and is of the order of 100 to 600 watts for each square metre of the orchard, significantly more than would be required to heat only the crop.

Irrigation can increase frost risk if it is followed by extensive daytime evaporation. Under tree irrigation at night during a frost has much the same effect as burning fuel. Irrigation water can maintain the surface temperature near or above freezing, convection from the surface warms the air, and air-to-crop convection keeps the crop warmer than it would have been, but the crop always stays colder than the surrounding air. Water logging of the soil may be a problem.

CROP HEAT BALANCE

The heat flow per unit area for a crop in a heated orchard is

$$Qr = Qc+Qe+Qh$$

Where Qh = heat from combustion

The heat supplied by the heaters is partitioned between the radiation and convection terms. The radiation component of Qh can be calculated in principle by summing the contributions of the heaters, knowing their temperature, emissivity and radiation patterns. If the radiation from the heaters exceeds the heat lost by radiation to the sky the crop will warm above the surrounding air.

Calculation of the convective and latent heat fluxes Qc and Qe requires the air temperature at crop height to be known. The air temperature at crop height can be related to the heater output if proper allowance can be made for all the losses such as heating air above the crop or air that is carried away by wind without coming near the crop.

A method of estimating the heat required for frost protection using heaters, based on seven variables, was developed by Crawford in California, USA in 1964 (Martsolf 1979). Nomographs were presented to allow several of the terms to be determined.

A model that computed crop temperature in a heated orchard was developed in Pennsylvania, USA in 1978 (Welles et al 1979). It indicated that a radiative heat component of 20% could be as effective as the convective heat flux in still conditions and much more effective in wind.

SMUDGE POTS

Smoky fires have been used for centuries in Europe for frost protection. It was erroneously believed that the smoke or 'smudge' was an effective heat 'blanket' that added to the heating effect of the fires. This idea persisted with the arrival of the smudge pots of the late 19th Century, but smoke particles are too small to scatter infrared radiation well enough to make an effective blanket. Crude oils and later fuel oils have been burned in open-topped 'lard pails' of 6 to 16 litres capacity. The pivoting lids of some pails have two functions. They keep rain out when fully closed and control the burning rate when partially open. A full pail with the lid wide open burns for about three hours, so refilling may be necessary at least once during a severe frost. Some pails use two lids, a full removable lid and a removable triangular partial lid or 'spider' to reduce the burning rate to about half that of an uncovered pail.

The radiant heat from a lard pail may be only 6% of the heat produced, the other 94% going into the surrounding air. A higher radiant heat output would warm the crop much better than does hot air. Better combustion efficiency would reduce the soot or 'smudge' output and also reduce the amount of fuel used. Smudge pots however have two very significant advantages: they are possibly the cheapest and simplest reliable frost fighting equipment available.

A 6-litre pail burns at a maximum rate of about 20kW and a 12 litre at about 40kW. They are typically spaced uniformly throughout an orchard with extra pots around the edges. Up to 300 pots may be used per hectare, producing up to 600W/m^2 to cope with the heaviest frosts. Only half the pots may be fired at a time, to allow for refilling. Air temperature at screen height can be raised by up to 4°C.

STACK HEATERS

Improved oil burning heaters were developed in California USA in the 1930's to reduce air pollution. They give a similar amount of heat to a smudge pot but burn with a nearly smoke-free flame. Several variations of the basic design have been successfully used. All have a sheet metal chimney or 'stack' from 150 to 750mm high and 150 to 200mm wide. The heat from the chimney is preferentially radiated horizontally towards the crop rather than towards the sky or the ground. About 20 to 30% of the heat is radiant. The oil is vaporised by the fire in the bowl and burns in the stack where extra warmed air is introduced to allow complete combustion.

Stack heaters are readily adjusted to burn from 1 to 4 l/h, giving 10 to 40kW per heater. At the higher burning rates they are less efficient, produce more smoke and have a reduced life. Optimum performance is at a rate of about 20kW, burning two litres per hour. The comparatively large reservoirs of the stack heaters allow them to burn all night without refilling. Upwards of 125 heaters have been used per hectare to produce about 500W/m^2 at a maximum burning rate of 500 l/ha/h. Air temperature at screen height is raised by perhaps 5°C. A typical result is shown in Figure 10.1 (Young 1947) where the number of heaters fired was increased as the night progressed and the frost hardened.

A very large oil-burning radiant heater was developed in the USA. It was tested at the National Institute of Agricultural Engineering in Australia (Courshee 1950). There was an approximately exponential relationship between available protection and distance from the heater. It 'covered' 0.2ha but a major disadvantage was that nearby trees were scorched and more distant ones frozen.

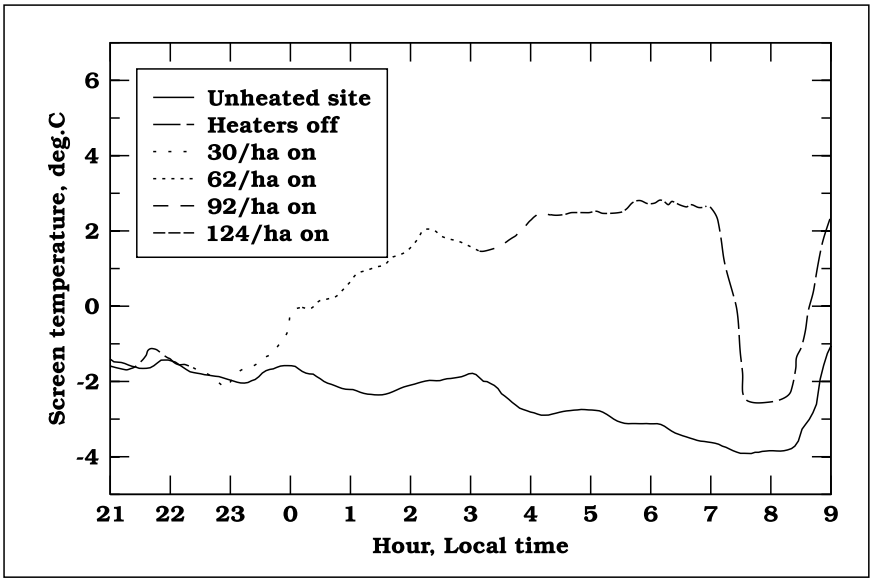

FIGURE 10.1. Screen temperature in an orange grove equipped with 124 double stack oil heaters per hectare, and at an unheated site nearby, during a hard radiation frost in California. The number of heaters fired was increased as the frost hardened. (After Young).

SOLID-FUEL HEATERS

Briquettes made from coal, coke, turf, wood shavings, sawdust, baled straw and various other fuels have been used for orchard frost control. Heaters are made of vertical cylinders of sheet metal about 600mm high and 300mm diameter with a grate at the bottom and an open top. About 25 briquettes are loaded into the heater before firing and replenished by adding about eight briquettes per hour. The heat output (about 10kW) is half that of a stack heater or a smudge pot so up to 250 briquette heaters may be required per hectare. Coke heaters have been found to give up to 40% radiant heat, proportionally much more than oil burners.

PETROLEUM WAX HEATERS

The Citrus orchards in the Rio Grande Valley, Texas, USA were badly hit by the 'Blue Northers' (advective freezes) in 1949, 1951 and 1962. Some ten million Citrus trees were destroyed in January 1951 and in 1962 the industry was reduced by 30% (Hensz 1969). The use of many small carefully placed heaters with high radiant output was advocated following the disastrous freeze in January 1962. Three small under tree heaters were developed to protect Citrus trunks and branches. Petroleum wax was burned from a wick in a tray or a large candle or else petroleum coke bricks were fired in the open (Turrell 1973).

WAX CANDLES

A typical wax candle is a 6.35kg cylindrical block of wax in a waterproof cardboard container about 250mm high and 200mm diameter (a 7.5 litre ice cream container). A fibreglass wick

floats on top and the sides burn away. A single candle will burn for 8 hours at an average rate of about 10kW, half that of a stack heater.

European experience with wax candles suggests that four candles beneath a single tree can protect it from a frost of -9˚C. From 400 to 600 candles are required per hectare depending on frost severity and site. Air temperature is raised by 1 to 4˚C for a heat output of 400 to 600W/m^2 (Bagdonas et al 1978).

WAX TRAYS

Open-topped sheet metal trays 430mm x 300mm x 65mm holding 6.35kg of petroleum wax will burn for some ten hours at a rate of about 6 kW. Smaller and deeper breeze concrete trays, 235mm x 235mm x 200mm filled with 4.5kg of wax, have a similar heat output. In the metal tray the wick is made of rock wool, the concrete is its own wick.

PETROLEUM COKE BRICKS

A petroleum coke brick measuring 200mm x 100mm x 50mm, weighing approximately 1kg will produce about 7kWh when fully burnt. A two-brick package burns for four to five hours at an average rate of 2.5 to 3 kW. Three-brick packs burn for five to six hours at 3.5 to 4kW. About 25% of the heat is radiant.

PIPELINE HEATERS

Stack heaters have been modified to burn oil carried around the orchard by a pipe system. Others have been especially designed for such systems and used a drip feed. More recently heaters of from 25 to 60kW output, capable of burning fuel oil, Diesel oil, CNG or LPG have been introduced. Pipeline pressure may be 700 to 1,400 kPa. As with the other forms of crop heating, radiant output should be maximised. Radiation should be directed towards the plants. Up to 600W/m^2 may be required and the burners should be many and small rather than few and large.

An interesting natural gas system (LPG) for protecting a 20-hectare apple orchard in Maryland, USA has been described (Valli 1970). Two thousand simple windproof gas burners (100/ha) were connected to a 50mm gas main by 19mm lateral feeders. About 20 heaters were connected to each feeder. The heaters were simple burners set on the ground with slightly conical cylindrical sheet metal chimneys 685mm high and approximately 280mm diameter. The chimneys were wrinkled to increase surface area from 0.6m^2 to more than 0.65m^2. The radiant heat would have been about 20% of that released by combustion.

Changing the gas pressure controlled heat output. Pilot flames were lit before critical temperature was reached, ready for immediate increase in heat output when required. With a pressure of 7kPa the pilot flames produced 3kW per heater. The useful output began at 11kW per heater with 35kPa gas pressure. Optimum output was 38kW at 140kPa rising to a maximum of 56kW at 245 kPa. The heating rate was therefore readily adjustable between 110 and 560W/m^2.

The system was tested in spring 1969 on a clear calm night when a very strong inversion formed (about 10˚C up to 30m). The ‘heating effect’ (from air temperature measurements) in the fruit zone of the apple orchard was maintained at 2.2˚C or more all night, following the lighting of the heaters at 11.30pm. Temperatures in the orchard rose about 2˚C in the first hour and a half after lighting. The gas supply pressure was 35kPa, which would have

given about 110W/m^2. As time progressed and temperatures outside the orchard fell, the gas-burning rate was increased to maintain orchard air temperature near 0˚C. At 2.30am the pressure was increased to 70kPa, giving perhaps 220W/m^2 and at 4.00am to 105kPa to give about 300W/m^2 until sunrise. The maximum 'heating effect' was 3.3˚C for a brief period 2.4m above ground and the minimum temperature recorded at the 1.5m level was -0.6˚C, which was 4.4˚C above the -5.0˚C recorded outside the orchard.

ELECTRIC HEATERS

As a rule frost protection using electric heaters is entirely impractical because of the enormous amount of energy required. The equivalent of one to six single-bar heaters (1 to 6kW) would be needed for every ten square metres of ground. A single 10 hectare orchard would use as much power as a town of 1,000 to 6,000 houses in which every stove element was running, including the oven (10kW/house). Nevertheless electric heating has been used for frost control where only a very small area is to be protected, such as a single tree. Draping a cover over the top of the tree and placing one or more electric lamps or heaters below may reduce heat loss. Subsoil electric heating is used to grow some greenhouse crops, where heat loss can be kept low.

HEATER DESIGN

Frost fighting heaters should be carefully designed for optimum results. The fuel must be burned at maximum efficiency using a minimum amount of fuel and giving little smoke. Infrared radiation must be maximised and directed towards the plants. Radiation from the heaters becomes more important as wind speed increases because the orchard air does not warm up as much as when it is calm. A radiant heat flux of the order of 50 to 100W/m^2 of the plant surfaces will be required for them to reach the temperature of the surrounding air. With lower radiant heat output the crop will always be colder than the air surrounding it and the air has to be heated more to give the protection required.

The simplest suitable infrared radiator is a tall vertical cylinder of oxidised metal that will preferentially throw heat horizontally. It should not be so hot that it scorches nearby vegetation or burns out too quickly. The practical limit is incipient red heat of the order of 500˚C. Heat may be wasted if warms the soil near the heater. Mounting an orchard heater above the centre of an aluminium foil soil cover about 3m diameter increases the radiation reaching the crop (Fritton and Martsolf 1980). The equivalent of 16 to 27% extra radiation was produced by this simple technique.

The maximum heat that usefully can be employed depends on the strength of the temperature inversion. Experiments have verified the hypothesis that many small heaters give better frost control than a few large burners. When large heaters are used the hot plumes may 'pierce the ceiling' and result in lower-than-desired protection; mixing with cold air brought up from below may cool the air above ten metres. This unexpected result is due to the strong convection set up by the large hot plumes from the heaters. The plumes from small heaters rise slowly and do not cause extensive mixing.

The air below 2m may be up to a degree warmer when 3kW petroleum coke bricks are used in preference to 30kW oil burning stacks, as shown in Figure 10.2 (Bagdonas et al 1978). More significant is that the radiant heat can warm the leaves more than 1˚C above the surrounding air provided the heaters are not screened from the leaves.

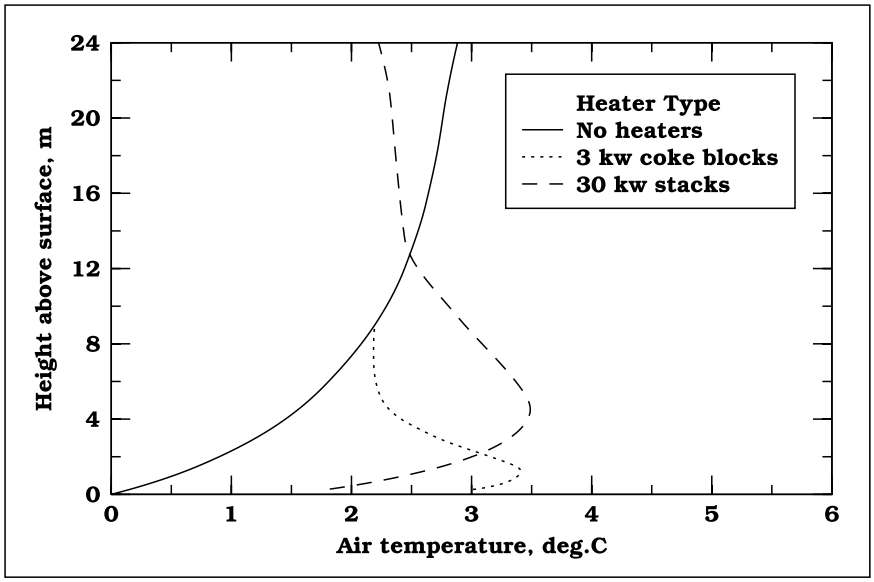

FIGURE 10.2. Typical air temperature profiles observed in and above areas heated by either 30kW oil-burning stacks or 3kW petroleum coke bricks during radiation frosts, showing that the small heaters give better frost protection close to the surface. (After Bagdonas et al).

UNDERTREE IRRIGATION

Flooding or irrigating an area during the day may result in colder than normal surface temperature if significant evaporation occurs. Continuous irrigation at night during a light frost may sometimes give adequate crop protection. Irrigation wets the ground, increasing the heat conductivity. This allows soil heat to reach the surface more readily and keeps it warmer than if the soil was dry.

The heat required to maintain the ground surface at -0.5°C in the hard frost considered in Chapter 6 is given by the model

$$Qrn = Qc+Qe+Qg+Qs$$

where Qs = heat flux supplied by the water

The heat flux supplied by the water is a combination of sensible heat released as the water cools to the freezing point and latent heat released as it freezes. When all the water reaching the ground freezes and brings the surface up to -0.5°C the surface will be losing 88W/m^2 by radiation and 20W/m^2 by convection and evaporation. It will be receiving about 22W/m^2 by conduction from below ground so the heat released by freezing has to be about 86W/m^2. If the surface is to be held at or above 0°C and none of the water is permitted to freeze, rather than allowing it all to freeze, the quantity of water required is increased by up to the ratio 80/T where T°C is the temperature of the water leaving the irrigation nozzles.

If the air above an irrigated area could be kept there and no air was exchanged with the surroundings (an 'infinite orchard') then water applied at an equivalent rainfall rate of less than 1mm/h could, if all frozen, supply up to 100W/m^2 and maintain the surface at 0°C all

night. The air above the surface would be warmer than 0˚C, possibly 2˚C at screen height and tree crops could be kept just above freezing. In the real world the air in an orchard is quite quickly replaced by unmodified air drifting in from the side or passing over the top. The air in a 10ha square orchard would all be replaced in less than five minutes by a wind of the order of 1metre per second. The soil below the surface may also have cooled below freezing point before sprinkling is commenced. In these circumstances much more than 1mm/h of water has to be applied to raise the surface temperature and maintain it at freezing point during a frost.

The air drifting into an orchard in a frost may be below freezing at crop height. It will be warmed as it crosses the irrigated surface but its temperature may not rise above 0˚C at ground level and is unlikely to reach 2˚C a metre above ground unless the sprinkled water is quite hot. It is quite likely to stay below freezing across the whole protected area when the orchard is small. Under tree irrigation supplies only the heat required to maintain surface temperature near freezing point. Crop temperature will always be cooler than the air surrounding it and may fall below 0˚C. Crop temperature depends on the height of the crop above ground, the temperature of the unmodified air and the prevailing wind speed. Low-growing crops such as strawberries may be protected quite well but a crop more than a metre above ground in a small orchard may receive little benefit from under tree irrigation.

Under tree irrigation with a 'hand move' aluminium sprinkler system was tested for one night in a 12-year-old almond orchard in California USA, in the winter of 1986-87 (Connell and Snyder 1989). Soil surface temperatures were measured with an infrared thermometer held about 1m above ground. Minimum soil surface and air temperatures outside the test area were about -2.8˚C and -3.0˚C respectively. The wind speed was less than 1m/s during the test. Variable sprinkler head spacing simulated sprinkler rates of 2.0, 2.2 and 4.4mm/h. Maximum effect was observed near the centre of the test area where the sprinklers were spaced on a 16.5m square grid and the equivalent rainfall rate was 4.4 millimetres per hour. Surface temperature depended on wetness of the surface. The lowest reading was over soil that appeared to be dry, about -2.2˚C. The highest reading was -1.1˚C, over water that had ponded but there is no mention of ice on the ponded water. This test gave a maximum increase in surface temperature of 1.7˚C and 0.6˚C in air temperature (measured with 'minimum glass thermometers in modified orchard minimum recording thermometer shelters' at an unspecified height) for an equivalent rainfall rate of 4.4 millimetres per hour.

Micro sprinklers were used for under tree irrigation to protect a plot of young Citrus in Florida, USA in 1981 (Parsons et al 1982). Approximately 5.4mm/h of water (water temperature was 20˚C) was used and air temperature was measured 1.2m above ground. Air temperature was 0˚C sixteen metres in from the upwind edge of the plot when it was -2˚C outside about midnight. By 3am the air in the plot had fallen to -2˚C when the lowest temperature outside was -4˚C. It was assumed that perhaps 400 watts was released to each square metre of the surface by the irrigation water as about half of it froze. There are two ways of looking at the result of this experiment. The first is that under tree irrigation at a rate of 5.4mm/h released about 400W/m^2 and kept the air 1.2m above ground 0.5 to 1.5˚C warmer than if there was no irrigation. The second is that the air temperature at 1.2m was able to go at least as low as -2˚C when unmodified air coming into the plot went down to -4˚C.

Air temperature 2m above ground was measured in orchards protected by under tree irrigation using both impact-drive and micro sprinkler systems in Prosser and North Tieton, Washington USA in 1986-88 (Evans et al 1988). Irrigation rates were 3mm/h impact drive in a 28ha orchard and about 0.9mm/h micro sprinkler in a 2ha orchard. The micro sprinkler system used nozzles giving 1.87mm/h but only about 50% of the area was covered because

they had been used to replace the impact-drive sprinklers of an existing system. No significant temperature difference was found between the air at 2m in the micro-sprinkled orchard and the air outside the sprinkled area in a frost that brought 2m-air temperature to about 0 to 2.5˚C. The impact-drive system held 2m-air temperature to 0˚C when unmodified air reached -1 to -2.5˚C in another frost. A model was developed to explain the observations in the 28ha orchard at Prosser (Davies et al 1988). The maximum increase in air temperature 1 and 2m above ground was predicted to be 1.7˚C for an equivalent rainfall rate of 2.5mm/h. The observed temperature increases were widely scattered within +1 and -1˚C of the predicted value.

CHAPTER ELEVEN

WATER SPRINKLING FROST CONTROL

INTRODUCTION

Direct crop heating by continuous water sprinkling is the most reliable and economic practical active method of frost protection. Provided that the amount of water falling on the crop is sufficient to maintain a wet ice surface the latent heat released keeps the crop temperature between -0.5 and 0˚C irrespective of the frost severity. Water has been applied at equivalent rainfall rates between 0.8mm/h and 6mm/h (6mm/h = 6 litres per square metre per hour or 60 tonnes per hectare per hour) and has held crop temperature as much as 6˚C above that of unprotected crops. If all the water applied at 6mm/h freezes on the surface of the ground it releases about 600W/m^2 (watts per square metre). At the maximum application rate of 6mm/h the power required to drive the pumps is about one watt per square metre.

In the traditional system water at a pressure of about 480kPa is sprayed from rotating nozzles on top of 5m poles on 20m centres at a rate sufficient for adequate protection in the hardest expected frost. The system is wasteful in light frosts because it uses much more water than necessary. It may also cause water logging in some soils. Relating the quantity of water sprayed to the degree of protection required would be more satisfactory. Developments in mini sprinkler design and pulsed water control allow 'targeted' sprinkler systems to be designed to cope with any reasonable requirement, giving absolutely reliable protection with a minimum amount of water.

PROTECTED CROP HEAT BALANCE

A crop protected by freezing of water from overhead sprinkling is warmer than its surroundings. It loses sensible heat Qc by convection and latent heat Qe by evaporation because it is held at about -0.5˚C while the air and dew point are a few degrees cooler. Three components of heat flux must be adequately modelled, radiant, sensible and latent. At equilibrium the heat supplied by the water striking the top surface of the crop must balance the heat lost, i.e.

$$Qs = Qc+Qe+Qr$$

where Qs = heat flux supplied by the water

The radiant heat flux Qr outwards from the crop is by convention assumed to come from the upper surface only and typically may be about 50 to 80W/m^2. Some of the sprinkled water evaporates in the air, cooling it and raising the dew point temperature. The sprinkling rate must be increased to allow for this. Few estimates exist for the extra water required even though the supply may need to be doubled. For each gram of water evaporating from the crop seven and a half grams must freeze on the crop to maintain the temperature. Heat loss from ice-protected apple buds to the surrounding air has been measured in a frost chamber and in the field (Hamer 1986). Heat transfer fell from about 35W/m^2/˚C at the commencement of sprinkling to a lower limit of 20W/m^2/˚C after several hours due to the build-up of ice on the buds.

When the 10mm diameter apple bud introduced in Chapter 6 is protected from the hard frost by freezing water it loses 260W/m^2, 86W/m^2 by radiation, 99W/m^2 by convection and

75W/m^2 by evaporation. The heat flux Qs supplied by the water is a combination of sensible and latent heat. A sprinkling rate of 1mm/h will release the equivalent of approximately 100W/m^2 to the upper surface of the crop and surroundings if all the water freezes (assuming that the water was at about 6˚C when sprinkled, 7W/m^2 sensible heat is released in cooling to 0˚C and 93W/m^2 latent heat is given up in freezing). This assumes that the sprinklers are distributed uniformly through the orchard, they give uniform coverage, all parts of the crop are equally exposed, none of the water striking the crop runs off and none evaporates. Up to 1.5mm/h and even more has been used to give the equivalent of 100W/m^2 to the upper surface to allow for non-uniformity of spray and runoff. Allowing 50% for runoff, non-uniformity, and wastage, the pump must deliver enough water to give an equivalent uniform coverage of one and a half times that calculated, or at least 3.9mm/h to provide the 260W/m^2 required.

SPRINKLING RATE

Several approximate methods have been proposed for calculating the water application rate for frost protection with overhead sprinklers, e.g. (Gerber & Martsolf 1979), (Barfield et al 1981), (Perry et al 1982), (Perry 1986). These methods are rather complicated and would have little practical application other than to define a maximum sprinkling rate because only one, two, or possibly three average rates are normally available. The sprinkler rates found to work may be tabulated as in Table 11.1 for vineyards.

TABLE 11.1

SCREEN TEMP. DEG.C.	APPLICATION RATE, mm/h WIND 0-0.5m/s	WIND 0.9-1.4m/s	WIND 2.2m/s
-1.7	2	2.5	4.2
-3.3	2.8	3.3	5.6
-5	3.8	4.6	7.6

STARTING AND STOPPING SPRINKLING

Sprinkling should be limited to the minimum time necessary because of the undesirable side effects such as water logging of the soil or tree damage from excessive ice loading. Freezing must usually be initiated as close as possible to 0˚C to prevent damage from non-equilibrium freezing of super cooled tissue and a high application rate may be required to keep the crop surface wet so that it does not dry and allow the temperature to drop below about -0.5˚C. Early in spring, when some plants can tolerate low temperatures, a low application rate may suffice, when insufficient water reaches the crop surface to keep it wet and its temperature drops several degrees below zero.

When the sprinklers are first turned on the air and crop temperatures in the protected area may fall towards the dew point over the next 15 to 30 minutes due to the evaporation of some of the sprinkled droplets. The danger is that the crop temperature may fall too low and it may be damaged before enough water freezes on the crop surface to bring it back up above the critical level.

Evaporation may cool a sprinkled crop to a damaging temperature if the sprinklers are not turned on early enough or turned off too early in the morning. The evaporative cooling will be greatest when the dew point is lowest and the temperature at which sprinkling is commenced must be raised in proportion to the depression of the dew point. Recommended

starting air temperatures for grapes rise from 1˚C to 4˚C when the dew point falls from -3˚C to -10˚C when sprinklers cover the whole vineyard area, and up to 2˚C higher if targeted micro sprayers are used.

When the sprinklers are turned off evaporation from the ice covering the crop cools it toward the wet bulb temperature, and if it dries below the wet bulb temperature it cools toward the frost point. The wet bulb temperature may also be below 0˚C before sunrise, so sprinkling should be maintained till the wet bulb temperature rises above 0˚C. There may be no need to continue sprinkling after the wet bulb temperature reaches 0˚C; it may merely hasten the melting of the ice and waste water. There may still be the danger of thawing damage if the Sun shines directly onto thawing plants and melts the ice too quickly to allow deplasmolysis to restore the cells to normal (Bleasdale 1973). To prevent thawing damage it may sometimes be necessary to maintain sprinkling for long enough about sunrise to make sure that thawing is completed before the Sun shines on the crop.

SUPER COOLING

Super cooling prior to ice nucleation occurs even when frost protection sprinklers are turned on before the crop temperature goes below zero. Figure 11.1 (John 1985) shows that the water on an artificial bud 3m above ground failed to nucleate to ice for about two hours after its temperature went below zero at 1am. Nucleation finally occurred when the bud temperature reached -1.2˚C at 3am and its temperature rose quickly to -0.2˚C. An artificial bud 1m above ground on the same tree nucleated at -0.5˚C at 1.30am within half an hour of going below zero.

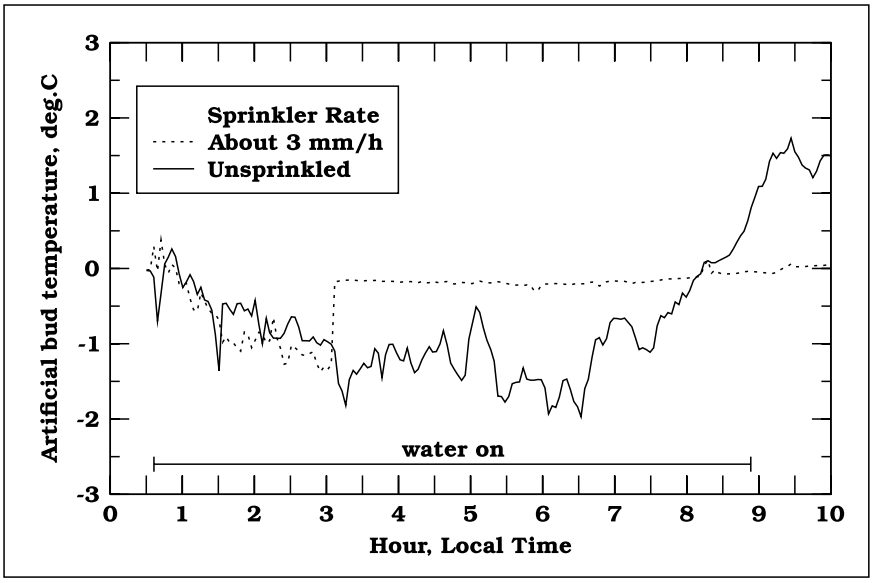

FIGURE 11.1. The temperature of an artificial bud 3m above ground sprinkled by targeted mini sprinklers, and an unsprinkled artificial bud at the same height, during a radiation frost at Earnscleugh. There was a delay of about two hours after the sprinkled bud temperature went below 0deg.C., before the ice nucleated at -1.2˚C. (After John).

GROUND WETTING

When a crop is sprinkled with water for frost protection most of the water finishes up on the ground where some or all of it freezes. When the sprinkling rate is adequate for protecting the crop it is more than enough to keep the ground surface wet; not all the water reaching the ground freezes and the surface temperature may rise slightly above 0˚C.

The sprinkling rate needed to keep the surface near 0˚C is about 0.9mm/h if all the water reaching the surface freezes. For a sprinkling rate of 2.6mm/h allowing 50% for wastage and runoff will require up to 3.9mm/h to be used. The ground is over watered, by up to 2.9mm/h, and stays wet and near 0˚C. Only in the case where the water is very warm can the surface temperature rise appreciably above freezing.

Water can be saved by 'targeting' the crop with mini sprinklers, leaving the area between rows without protection other than overshoot from the sprinklers and runoff from the ground below the crop. As the targeted area will probably be about a quarter of the total area the ground surface may still be over watered and stay near 0˚C.

INADEQUATE WATER

When the sprinkling rate is too low for the latent heat released by freezing to balance the heat lost by radiation, convection, and evaporation, the ice surface covering the crop will dry between rotations of the sprinkler head or between pulses if a mini sprinkler system is used. The average temperature of the crop will then fall until the heat supplied by the water just matches the heat lost and the technique may be considered to have failed. It has failed however only to maintain crop temperature above -0.5˚C. It may still keep the crop several degrees warmer than it would have been without protection. The icicles will be clear when the sprinkling rate is adequate but will be milky and may not completely encase the crop when sprinkling is insufficient to maintain a wet surface (i.e. insufficient for latent heat to supply all the heat required).

ON-OFF PULSING

Water must be supplied at an appropriate rate to match the expected frost. A practical maximum continuous sprinkler rate is 5mm/h equivalent rainfall. This will just keep the ice surface wet with minimum runoff and bud temperature will be between 0 and -0.5˚C in a frost where an unprotected bud will be about -5˚C. Should such a system be pulsed off the ice on a bud will dry over the next minute or so, the temperature of its surface staying above about -0.5˚C. Once the ice surface dries the bud temperature will fall below -0.5˚C at a rate determined by the size of the bud and its ice coating. The temperature may fall to the dew point, which could be low enough to damage the crop.

Water can be saved in light frosts by turning the water off once the buds have wetted to runoff and keeping it off until they just dry. It is then pulsed on again and the cycle repeated. A properly adjusted system will always maintain the buds above about -0.5˚C. When the ON time is too long excessive runoff occurs, when the OFF time is too long the crop will dry between pulses. A long ON time wastes water, a long OFF time allows the crop to cool below about -0.5˚C.

CONTINUOUSLY VARIABLE PULSE RATE

The water supply can be matched to requirement if the temperature of an 'artificial bud' is used to control an ON-OFF pulsed water supply. A system with variable pulse rate was tested at East Malling, UK in 1976 (Hamer 1980). The temperature of artificial buds in the sprinkled area was controlled by a rotating-head (impact-drive) system. Each sprinkler was pulsed ON whenever its artificial bud went below -1˚C. The rotation period of the heads was 40 seconds and the maximum continuous equivalent sprinkler rate was 3mm/h.

The temperature of natural buds cycled over a range of about one degree between water ON and OFF, cooling at about 0.4˚C/min between pulses of water. At one stage during a light frost with low wind speed a single pass of the sprinkler was apparently sufficient to bring the natural bud up about a degree, the supply was automatically switched OFF and it took nearly four minutes before the temperature dropped to the level that triggered the next ON period. The average equivalent sprinkler rate during this test was 0.8mm/h.

An unsprinkled artificial bud at screen height some distance outside the sprinkled area was used as a reference. No water was required for an unsprinkled artificial bud temperature down to -0.65˚C. Below this down to an unprotected artificial bud temperature of -3.0˚C an average rate of 0.85mm/h/˚C was required to keep the sprinkled buds at the control temperature (-1˚C).

There are several potential problems when a continuously variable pulse rate is used as at East Malling. These range from a failure to spray if the temperature sensing fails in the water OFF state to the water hammer and electrical problems caused by repetitive ON-OFF switching of very large pump motors. There may also be problems when ice builds up if only one artificial bud is used in a non-typical position for control. The 'inertia' of the ice load will lengthen the time constant giving longer ON times possibly leading to excess runoff and longer OFF times leading to excessive cooling of the crop. A practical system should be free of these potential problems so as to be 'fail safe'.

FIXED PULSE RATE SPRINKLING

Water must be sprinkled at an average rate that when continuously applied it would just match the freezing to provide complete protection in the coldest expected frost. When a sprinkler system applies water continuously at a rate that exceeds that at which the water freezes, runoff will occur, and water is wasted. The maximum thickness of the layer of unfrozen water that can remain on an ice-covered bud without runoff is of the order of 0.03mm (Gerber & Martsolf 1979). Wastage in less severe frosts may be reduced by cyclically pulsing the water off before the unfrozen layer thickness reaches runoff and then waiting until the ice almost dries before pulsing on again.

The cycle time Tc is then the sum of the ON and OFF times for pulsed operation during light frosts or early at night where less than the maximum amount of water is required,

$$Tc = ON + OFF$$

The minimum ON time, Tmin, for a pulsed sprinkler system, to bring the water layer to runoff will be that required to just build up a layer of water about 0.03mm thick on the crop, if none is lost by evaporation, and none freezes on the crop. Allowing for only the upper surface being able to collect the water, and if none freezes, the instantaneous sprinkling rate R (mm/h), required to build up a 0.03mm thick layer on both upper and lower surfaces may be given approximately by

$$R = (2*0.03*60)/Tmin$$
$$= 3.6/Tmin$$

where Tmin = the minimum ON time in minutes
and the factor 2 accounts for the two surfaces
(upper and lower) that must be wetted

To bring the water layer to the runoff thickness of 0.03mm with an instantaneous sprinkling rate R of 3.6mm/h the minimum ON time is one minute and for any higher sprinkling rate than 3.6mm/h the minimum ON time will be less than a minute. The sprinklers may then be turned off until the crop surfaces are almost dry and the cycle is repeated. Allowing for uneven distribution the minimum ON time would need to be shortened to prevent runoff from those parts of the crop receiving more than the average water.

With mini sprinklers equal ON and OFF times give two sprinkler rates, full (continuous) and half (pulsed) to match hard and light frosts respectively. The orchard can be divided into two equal-area blocks and two equal-capacity pumps are required. Either both pumps run continuously for maximum protection or one pump only is used, cycling between the two areas about once every minute so as to prevent pump damage during switching.

A system supplying a maximum of 5mm/h for a severe frost climate may have an ON time of 3.6/5 = 0.72 minutes. Three application rates may be appropriate and require three equal orchard areas, two pumps one twice the capacity of the other, or three equal pumps, and 1:2 ON:OFF and 2:1 ON:OFF water sequences in addition to continuous operation.

The most efficient cycle time in practice may be shorter than that calculated on the unverified assumption that the runoff depth is 0.03mm. Without definitive data it may be better to use a shorter cycle time than calculated. The minimum cycle time may be set by the mechanical constraints of the sprinkler system and the water loss from the lines during the OFF time. When the average sprinkling rate is matched to the requirement only at the maximum frost severity for the setting some wastage and overprotection occurs for all lesser frost severity.

TARGETED MINISPRINKLERS

The problems of continuously variable pulse rate and icing of the control thermometer are avoided with the fixed pulse rate ‘targeted mini sprinkler’ system developed at Lincoln, New Zealand. It was subjected to extensive orchard trials including a comparison with a conventional impact drive rotating head system at Earnscleugh (Clyde), Central Otago between 1984 and 1987 (John 1985) (John et al 1986) (John et al 1988).

Two mini sprinkler systems targeted 4m wide strips encompassing the rows of trees. The sprinkler heads were attached to elevated polythene pipes 19mm in diameter tied to support wires 4m above ground immediately above the tree rows. The average continuous sprinkler rate depended on height. It rose from 4.8mm/h at 1m to 5.8mm/h three metres above ground for the high rate system when running continuously. The height variation for the low rate system was similar and centred on 3.0 millimetres per hour. The rates were halved when the systems were pulsed for protection in light frosts.

The cycle time chosen for the Earnscleugh tests was 2 minutes, 1min ON, 1min OFF, for both mini sprinkler systems, one giving an average sprinkling rate of 3.0 and 1.5mm/h, the other giving 4.8mm/h continuous and 2.4mm/h pulsed. When running continuously the 3.0mm/h system maintained -0.4˚C down to an unprotected bud temperature of about -2.5˚C. When pulsed the system used 1.5mm/h and was able to keep artificial buds above

-0.4˚C for an unprotected artificial bud temperature of -1.5 to -2.0˚C. In the same conditions the 4.8mm/h mini sprinkler system coped above -4.5˚C when running continuously and -2.5˚C when pulsed at 2.4mm/h.

Plate 11.1 shows the targeted sprinkler section of the orchard after a night's sprinkling. The support poles and 19mm supply pipes running along each row of trees are clearly visible, as is the heavy ice loading on the trees. Careful inspection shows the ice on the ground to be only below the sprinkler lines with ice-free corridors between the rows.

Plate 11.2 shows typical mini sprinklers after several hours' operation. The icicles hanging from the tie clips holding the supply pipe to the supporting wire were formed by sprinkled water that hit them.

The conventional sprinkler system at Earnscleugh had impact drive rotating heads on top of 5m poles on a rectangular grid with 18m between centres with only one sprinkling rate, 4.4mm/h. This was adequate for frosts with a screen temperature down to about -5˚C. The rotation period of the impact drive sprinklers was nominally 40 seconds but as they iced up the period lengthened considerably. By the time the temperature of an unsprinkled artificial bud had dropped to -7˚C the rotation period would typically be between 52 and 165 seconds. Applying an equivalent rainfall rate of 4.4mm/h the impact drive system kept artificial buds above -0.4˚C down to an unprotected bud temperature of at least -5.0˚C.

Comparing the water consumption of the three systems showed that the saving for pulsed targeted mini sprinklers could be about 50% for typical radiation frosts.

Micro sprayers that produce a wetted strip pattern about 0.6m wide have been developed especially for grapevines, replacing the circular spray pattern of the rotating head mini sprinklers used at Earnscleugh. One such micro sprayer is the 'Wade Pulsator' that releases the water in short pulses to get larger droplets and use less water than if it sprayed continuously at the low rate required. Each micro sprayer delivered pulses at an instantaneous rate of about 21 l/h with water supply pressure of about 200kPa. Pulsators were mounted 0.56m above the cordon about 3.6m apart on every row of a Chardonnay vineyard near Los Alamos, California USA (Jorgensen et al 2003). Compared with the performance of a conventional sprinkler system on an adjacent vineyard maximum water saving was about 80%. This result is consistent with the practice where the vines in a typical vineyard cover about 25 to 30% of the area. The pulsing delivered water at about 6mm/h equivalent rainfall for about half the time, resulting in an equivalent rainfall over the vines of about 3mm/h. A claimed advantage of the system is that it uses about as much water as an under tree drip irrigation system so the same pumps can be used for both and it may not be necessary to have a large reservoir to store the water for frost protection.

ARTIFICIAL BUDS

The artificial buds used at Earnscleugh are shown in Figure 11.2. They were of similar construction to the artificial buds used at East Malling, UK (Hamer 1980). The thermal properties could be adjusted by placing close-fitting tubing with the required characteristics around the sensor body. They had similar radiant and convective heat transfer properties to deciduous fruit tree buds.

The temperature sensor was a readily available integrated circuit operated in such a way as to indicate 'bud' temperature to within 0.1˚C. The zener diode protected the sensor from failure believed to be due to lightning. With this simple precaution and using two-core flexible cable strung along a fence or laying on the ground these buds may be used reliably hundreds of metres from the control station.

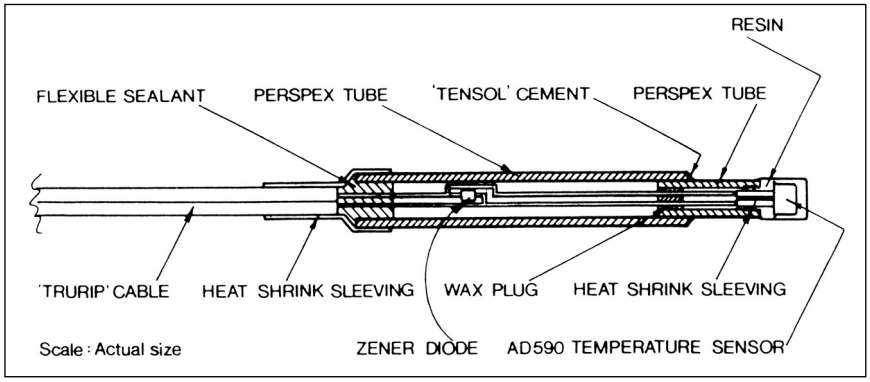

FIGURE 11.2. Diagram showing the construction of the artificial bud temperature sensors used at Earnscleugh. (John 1985).

Two control buds were located 1m above ground outside the orchard. When their temperature exceeded -2.6°C the mini sprinklers were pulsed and when it was below -2.6°C the mini sprinklers ran continuously. The impact drive system ran continuously during all tests.

SPRINKLING RATE UNIFORMITY

The uniformity of coverage of several makes of mini sprinkler was established in a large still-air laboratory at Lincoln (John 1985). The most uniform sprays were 'donut'-shaped. A modified sprinkler was eventually designed for field trials. It produced a spray volume of 41 litres per hour, sufficient for sprinklers spaced 2m apart to cover a hedgerow 4m wide at a mean equivalent rainfall rate of 4.8mm/h when mounted 4m above ground and used with a supply pressure of 200kPa. An alternative sprinkler giving 3.0mm/h was also developed. Both of these sprinklers were used in the orchard trials at Earnscleugh.

The effective rainfall rate from a mini sprinkler above a target tree increases with height of the buds because the water spreads out as it falls. The requirement on bare trees such as apricots however decreases with height because the air and buds are warmer higher up (the air and bud temperatures 3m above ground will be one to two degrees warmer than at 1m). The Earnscleugh tests assumed that buds 1m above ground would require most water and that protection at higher levels would be at least as good as at one metre.

As leaves grow the upper tiers will screen the lower parts of the trees and the radiant heat flux in a frost will decrease towards the ground. The screening can be so effective that the temperature profile in a citrus orchard is distorted. The air near the treetops in extreme cases can be colder than that near the surface. The treetops become the effective radiating surface and will be the first rather than the last to be frosted. Citrus and apple trees in leaf require more frost protection at the tops and less below.

Wind can reduce the coverage of targeted mini sprinklers. The spray can be deflected away from the trees with a resulting loss of protection. A test at Lincoln (John et al 1986), showed the effect of a crosswind on the water distribution of a row of targeted mini sprinklers for an average application rate of 4.6mm/h. The water reaching catch cans on the ground 2.6m below the sprinklers was halved in crosswinds of 2.9m/s. This could result in poor protection in a 'freeze' but 2.9m/s winds in a simple radiation frost would probably prevent reaching a sufficiently low temperature to cause crop damage.

LOSS OF CONTROL

The water used in sprinkler systems is usually 'irrigation' water taken from streams, rivers, or holding reservoirs. Such water will have dissolved solutes that depress the freezing point a few tenths of a degree below zero. (For comparison, the freezing point of seawater is typically -1.82˚C).

The temperature of sprinkled buds is depressed below 0˚C when solutes in the sprinkler water lower the freezing point. When the ice surface is kept wet and runoff occurs continuously the surface temperature will be of the order of -0.1˚C, the freezing point of the sprinkled water. When runoff stops, evaporation and freezing lower the surface temperature and it begins to dry, causing the solute concentration of the unfrozen water film to increase. If the average surface film thickness is reduced to a tenth of the runoff thickness by freezing and evaporation the freezing point of the water will be depressed to the order of -1˚C.

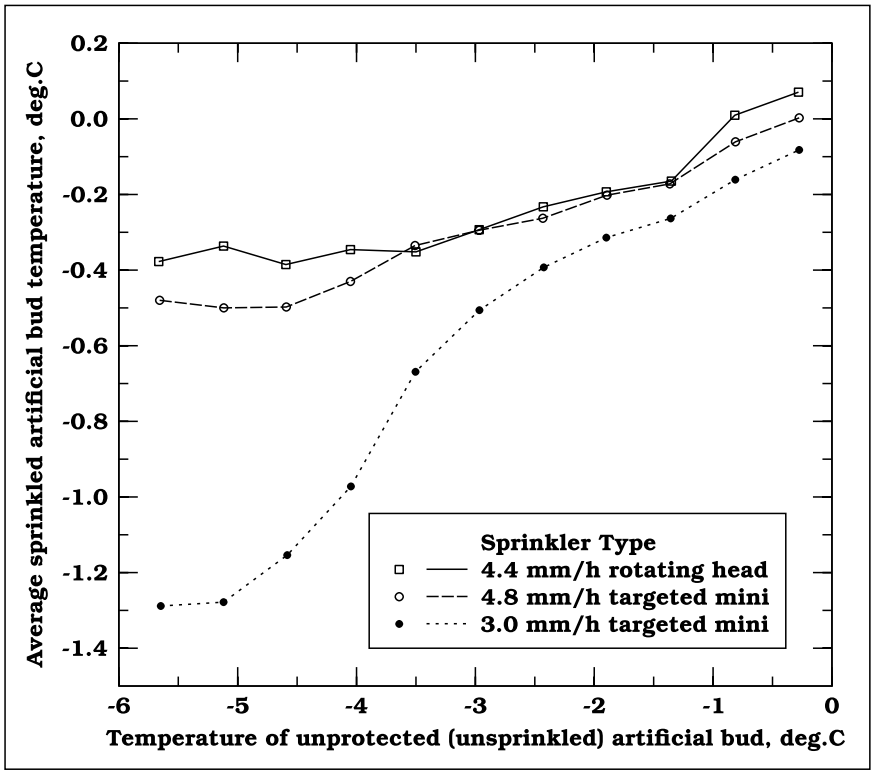

FIGURE 11.3. The effect of water sprinkling rate on the average protection given to artificial buds 1m above ground, as the temperature of an unsprinkled bud 1m above ground falls, for several radiation frosts at Earnscleugh. (After NZAEI).

Figure 11.3 (NZAEI 1987) shows the temperature of protected artificial buds typically falling from -0.1 to -0.4˚C when unprotected artificial buds fall from -1 to -3˚C. Bud temperatures are about 0.1˚C colder for 3mm/h sprinkling than for 4.4 and 4.8mm/h sprinkling. Protected bud temperatures fall below -0.4˚C when sprinkling rates are inadequate, as shown by the

data for 3mm/h. This may indicate the onset of drying, where the latent heat released by freezing is insufficient to keep the buds warm, and they must cool until the rates of heat loss and supply are equal.

The protection provided to artificial buds by the impact drive rotating sprinklers and targeted mini sprinklers was found to be similar as shown in Figure 11.4 (John et al 1986). It ranged from 0.7 to 1.3˚C/mm/h for application rates between 4.2 and 5.8mm/h in a frost that cooled exposed artificial buds to -4 to -8˚C. The earlier work at East Malling suggested that the better protection as the night progressed and the orchard cooled was due to a decreasing convective heat transfer coefficient as the ice built up on the buds. Another way of viewing the protection offered by sprinkling is shown in Figure 11.5 for Earnscleugh on the night of 13 August 1985. Failure to maintain bud temperature above -0.4˚C occurs for unprotected bud temperature below -2˚C for 3mm/h to below -6.3˚C for 5.8mm/h sprinkling.

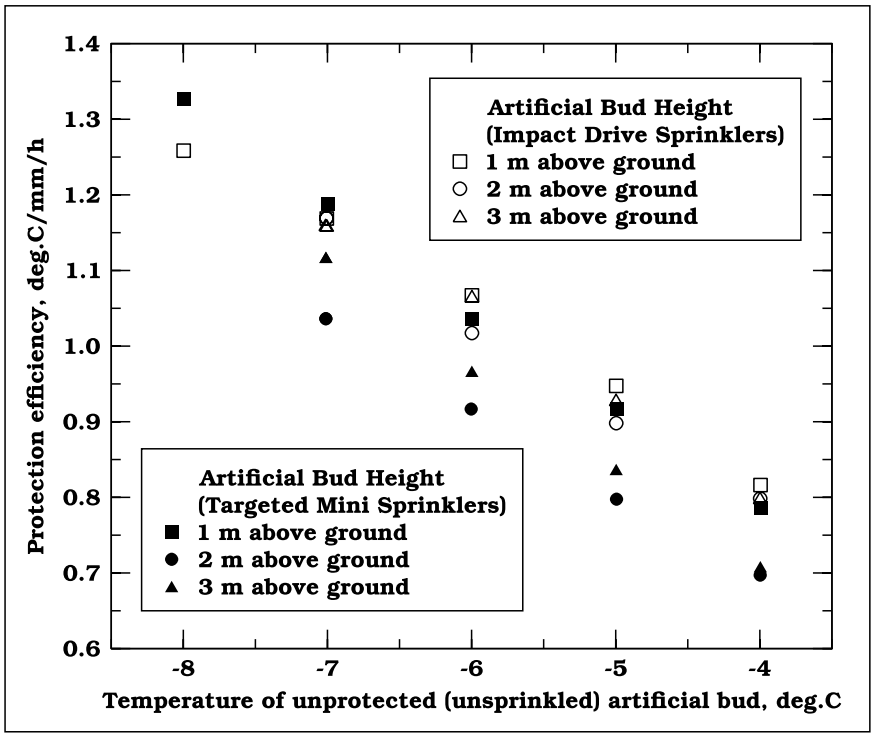

FIGURE 11.4. The frost protection of artificial buds provided by the water sprinkled by impact drive rotating head sprinklers and targeted mini sprinklers, as a function of the temperature of an unsprinkled artificial bud, in a radiation frost at Earnscleugh. (After John et al).

When the water supply just meets the requirement and the buds are being held at about -0.4˚C the average thickness of the unfrozen water film may be about half the runoff thickness. The depression of the freezing point may then be at least twice that of the water coming from the sprinklers. When evaporation is significant the freezing point is depressed even further. If half the water evaporates and half freezes the depression may be four times that of the water from the supply.

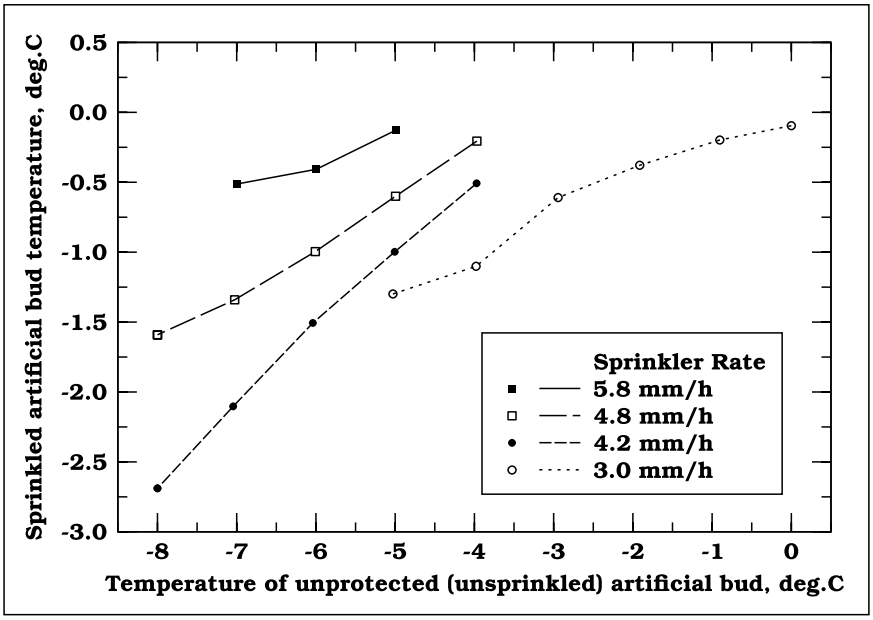

FIGURE 11.5. The temperature of artificial buds sprinkled by impact drive rotating head sprinklers and targeted mini sprinklers, as a function of the temperature of an unsprinkled artificial bud, in a radiation frost at Earnscleugh. (Data from John et al).

If sprinkling is maintained uniformly for a considerable time at an insufficient rate for runoff to occur the solute concentration of the surface film will gradually increase and can at least in principle reach saturation at the eutectic point when salt crystals will appear on the surface. If this unlikely event ever occurs the freezing point will be depressed to somewhere between -5 and -20˚C. In most sprinkler systems the water reaching the crop will arrive in pulses rather than uniformly, so the surface will cycle between wet and dry when the rate is insufficient to maintain it continuously wet.

The ice on sprinkled plants apparently changes character when the sprinkling rate is not sufficient to keep the surface wet. The icicles become milky and the covering may be incomplete. This occurred at Earnscleugh on 13 August 1985, a night when a hard radiation frost took air at screen height down to -7.5˚C at sunrise. Sprinkled artificial buds reached -2 to -3˚C, five to six degrees above unprotected artificial buds at the same height. The data suggest that buds that had remained above about -2.5˚C were encased in clear ice; the ice on those that cooled further was milky. This possibly indicates that the surface water was able to stay unfrozen down to about -2.5˚C and that the unfrozen layer thickness had been reduced by freezing to as little as a sixth of the maximum thickness at runoff assuming runoff ceased when buds were below -0.4˚C.

Photographs of the trees after sunrise on 14 August 1985 show the effects of too little and too much water. Plate 11.3 shows a tree that received insufficient water. The ice layer is white and incomplete. There are no visible icicles. The tree is immediately below an impact drive rotating sprinkler. Plate 11.4 shows a tree that received more than enough water. The large icicles indicate that runoff occurred extensively. It also shows one of the dangers of sprinkling for several hours in a severe frost. The ice became so heavy that a branch broke under the load.

The ice covering twigs and buds is shown in Plate 11.5. An icicle grows down from the lowest part of the central twig. The clear glassy appearance of the ice shows that the sprinkling rate was adequate to maintain a wet surface and a bud temperature apparently above -2.5˚C.

BUD COOLING RATE

The failure of the water supply at Earnscleugh for ten minutes one night allowed the cooling and heating rates of the ice-covered sprinkled artificial buds to be measured. The temperature of unsprinkled artificial buds was from -0.5 to -2˚C and air temperature must have been about -0.5 to -1˚C. Artificial buds typically cooled at about 0.1˚C/min from -0.5 to -0.8˚C and at 0.25˚C/min from -0.8 to -1.2˚C when the water supply failed.

When the water supply was restored at 3mm/h the heating from -1 to -0.5˚C was about 1˚C/min. The heating rate was in reasonable agreement with the cooling rates. Had the air been much colder, say -5˚C when the water supply failed the buds would have cooled by convection as well as by radiation, possibly more than 1˚C/min.

On several occasions during the tests at Earnscleugh the sprinklers were not turned on until the artificial buds had super cooled a few degrees below zero. The bud temperatures rose at about 0.23˚C/min when the sprinklers started. An example of this is shown in Figure 11.6 (John et al 1986), which also shows that the 4.2mm/h impact drive sprinkler failed shortly after midnight to maintain bud temperature above -0.4˚C when unprotected buds were at -4˚C. The targeted mini sprinkler applying 5.8mm/h maintained bud temperature above -0.4˚C until about 5am when unprotected buds were -5.5˚C.

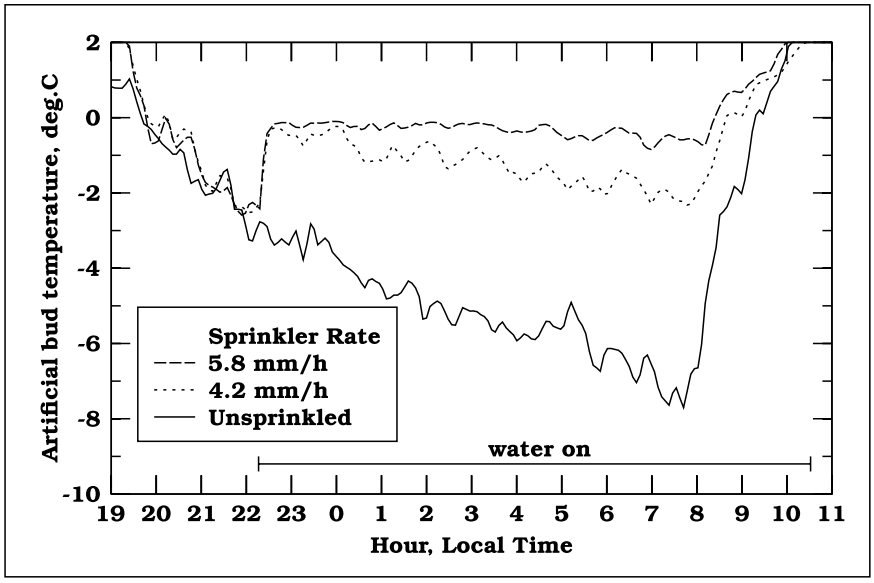

FIGURE 11.6. The average temperature of artificial buds 3m above ground sprinkled by impact drive rotating sprinklers, and by targeted mini sprinklers, and an unsprinkled artificial bud at the same height, during a radiation frost at Earnscleugh. (After John et al).

CHAPTER TWELVE

ARTIFICIAL FOG FROST CONTROL

INTRODUCTION

It has long been known that frost rarely damages plants on foggy and cloudy nights. Fog scatters outgoing infrared radiation back towards the ground with the result that the surface temperature may remain above freezing. Many attempts to induce natural fog before the temperature fell to the danger level have been tried but found wanting.

Artificial fogs have been made for frost control but they too have generally failed to be a practical proposition. Close scrutiny of the reports of fogging experiments shows that effective radiation reduction was rarely achieved and that air drift was always a problem. There is little evidence that effective air temperature control ever was achieved. There are clear indications that the latent heat of fusion of the fog water contributed significantly, if not wholly, to the maintenance of safe crop temperature. The fog was freezing on the crops in the same way as the water from an overhead sprinkler.

SMOKE PARTICLES

Some of the early frost protection experiments made fogs from smoke. The smoke particles that are so effective in reducing visibility were believed also to be useful for frost protection. 'Smudging', the production of smoke rather than heat by frost fighting burners was practised for centuries but eventually shown to be inappropriate.

The size distribution of smoke particles depends on the source. Sooty smokes have very fine carbon crystals of about 0.005 to 0.02um radius. In dry smokes the particle sizes are of the order of 0.1um and in oily smokes droplet radii can exceed 0.2um. Soot particles can agglomerate to sizes more than 0.5um under certain circumstances. The largest radius of most smokes is generally less than 0.5um, an order of magnitude too low for effective scattering of long wave infrared radiation.

NATURAL FOG

The effectiveness of a fog in frost fighting is a function of the droplet size. Natural fogs and clouds typically have particle radii from 0.1 to 10um, with most droplets having radii near 3.5um. A water fog has been found to be over ten times more effective than smoke particles in scattering infrared radiation (Mee & Bartholic 1979). Fog has a dramatic effect on frost temperature. The major effect when a fog or cloud comes overhead has always been assumed to be that there will be a reduction of radiant heat loss from the Earth. It is then implicit that the surface temperature will rise and along with the surface the air in the first few metres will warm up. A crop must also heat up because it is surrounded by warmer ground, warmer air and a warmer sky (in this case the upper portion of the fog layer). A frost study at Canberra, Australia in winter 1984 showed the effect of natural fog on air temperature 5mm above grassed, wet and dry soil plots. The sudden change in conditions at 3am in Figure 12.1 (Leuning & Cremer 1988) occurred when radiation fog enveloped the site, reducing heat loss to a low value. Cooling at 0.5°C/h changed to warming at 2.2°C/h and all the plots were frost-free by 3.30am. The temperature of Eucalyptus seedling leaves rose to equal air

temperature because the radiative heat loss from the leaves to the sky was reduced to nearly zero.

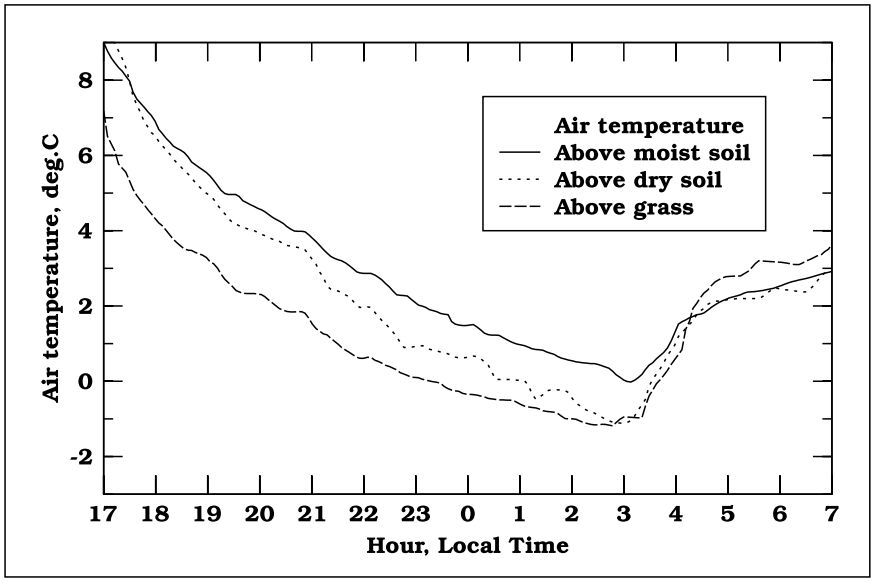

FIGURE 12.1. Temperature of the air 5mm above 25mm-tall grass, dry soil and moist soil in a radiation frost, showing the effect of the onset of radiation fog about 3am. (After Leuning and Cremer).

Attempts have been made to induce natural fog or cloud for frost protection. New Zealand Maori legends prescribe the procedure and incantations to be used on a clear starry night to cause the sky to cloud over and prevent a frost. A firebrand is waved vigorously around to an accompanying charm and the sky clouds over, averting the frost. A similar brand-waving ceremony has been performed on the west coast of Ireland (Best 1996). Hygroscopic chemicals have been used in attempts to provide condensation nuclei (seeding) in the hope that a liquid water fog would be induced to form from the water vapour in the air. This fails because there is not enough water vapour present. Fog would form naturally with dew on exposed surfaces and frost would be averted if sufficient water vapour existed. The air would need to be supersaturated, the relative humidity greater than 100% and air temperature below dew point for seeding to be effective. The magnitude of the problem can be seen by consideration of the amount of water involved. At 0.5˚C saturated air holds about $5g/m^3$ of water vapour. An effective fog layer would need to contain about $5g/m^2$ of free water droplets. If the layer were 10m deep the average fog density would be $0.5g/m^3$. The air to a height of 10m before nucleation would have to be supersaturated by 10%, an impossibly high value and air drifting into the protected area would also have to be continually nucleated.

FROST-FIGHTING FOG

The first experiments in frost fighting with artificial fog were summarised in 1979 (Mee & Bartholic 1979). The summary included a 1968 report of experiments with ‘Frostop’, a fog covered with cetyl alcohol to suppress evaporation, in the South Yakima Valley, Washington USA. The generators produced a fog by boiling water that was so thick that it obscured a

hand held out in front of a face. Subsequent 'Frostop' tests in 1969-70 and 1970-71 winters in California USA experienced trouble when wind blew the fog away from the measuring sites some 90m from the generators. A spokesman for the 'Frostop' manufacturers in 1972 is reported to have said in an interview, "We are still using the fog system in the Northwest, but we have abandoned it as far as California is concerned. The air currents were too much for us and there was no way we could put and keep the fog where we wanted it."

Making a fog by mechanical atomisation of water requires the least amount of energy. A practical fog generating system developed in the USA has been patented (Mee 1977). Highly filtered water is forced at high pressure (more than 3.5MPa) through a very large number of very small nozzles of about 250um diameter. The water impacts onto the tips of pins that break it into droplets of the size desired. Each nozzle produces about 1.4g/s of fog. The fog droplet size distribution of 'Mee' fogs used for frost fighting has been measured in orchards about 50m from the fog generators. The 'mean volume diameter' measured at Avize, France in 1982 showed 90% of drop radii ranging from 1 to 6um (Itier et al, 1987). The variation of 'droplet number density' with radius was measured on a clear night in an orchard near Hamilton, New Zealand in 1985 (Fisher et al 1985). It was found to be a good approximation to a modified gamma distribution (Diermendjian distribution). An example is shown in Figure 12.2 (Smith & Knox 1987). The radius of maximum droplet number density, the 'critical radius' 2.5um, was about five times larger than the optimum suggested by analysis yet the fog was found to be very effective. The power required to convert $1m^3/h$ of water to fog by this method is about two kilowatts and adds little heat to the air in the orchard.

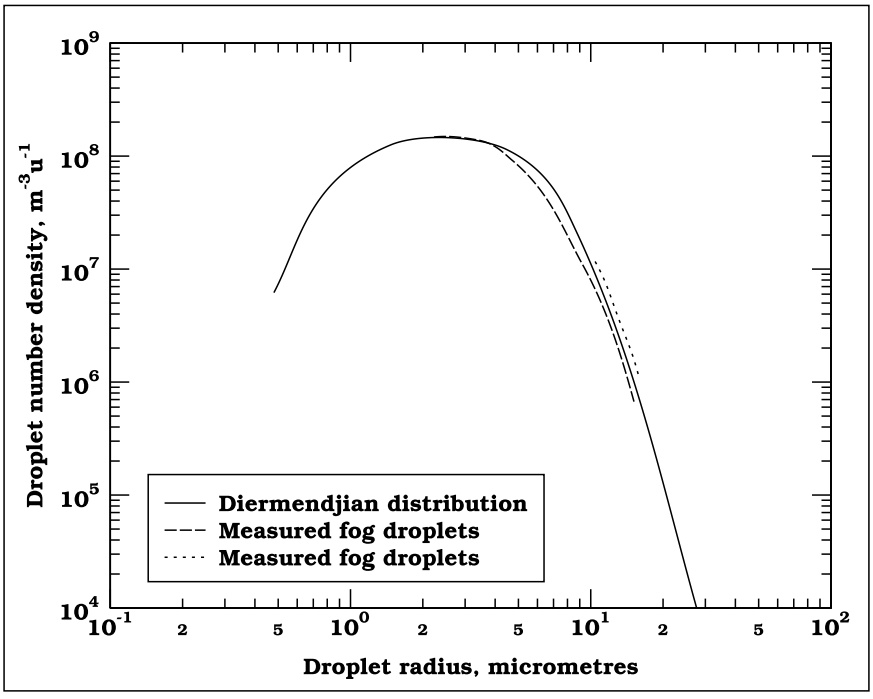

FIGURE 12.2. Comparison of 'Mee' fog droplet size distributions measured on a clear night near Hamilton with a modified gamma distribution (Diermendjian distribution). (After Smith and Knox).

'Mee' artificial fog was employed for frost protection in a Champagne vineyard at Avize, France on nine occasions in 1982 and 1983 springs (Itier et al 1987). Fog was generated by 100m long lines set at right angles to the prevailing wind, using from 330 to 990 impact-pin nozzles 6 to 8m above ground. Water consumption was between 1.5 and 5m^3/h. A layer of fog 1 to 3m thick was produced close to the surface. The prevailing wind blew it into a long tail extending 200 to 500m from the lines, normally covering an area of 1 to 3ha for each 100m length of line. The typical prevailing wind direction for the 1983 tests differed from that for 1982 so the fog generally covered different areas in the two seasons.

Artificial fog was generated by the 'Mee' process on several clear frosty nights in an apricot orchard at Roxburgh, New Zealand in spring 1981 (Ireland 1984). Two 40m lengths of fog line were suspended at right angles about 8m above ground. Each length of line carried 364 fog nozzles spaced 100mm apart. The flow rate with all 728 nozzles operating was about 3.6m^3/h. Plate 12.1 is a flash photograph showing the fog issuing from the nozzles. When wind speed was very low the fog wafted in all directions, falling from the lines in a short distance, as shown in Plate 12.2. With increased wind speed the fog streamed horizontally for over 10m in a 40m-wide plume, without mixing or spreading sideways, the lower edge not falling to the ground until it had travelled some 50m. The upper edge of the fog layer settled below 6m within the first hundred metres. Then the height of the upper edge decreased monotonously with distance. Fog was still readily identifiable by torch light some 300m from the point of release. Plate 12.3 is a panoramic view of the fog just before sunrise on such an occasion. The droplets that were too large to remain in the air fell quickly, making the ground in the immediate vicinity of the fog lines very wet.

A shortcoming of the technique of producing fog at a set location is that the distribution of the fog across the orchard depends on the prevailing wind, as was shown by the experiments at Avise and Roxburgh. Where the wind speed or direction is variable little control of the fog distribution is possible. This problem was addressed by an experimental fog machine in an orchard near Hamilton, New Zealand in winter 1985, when 1,200 'Mee' fog nozzles were mounted 100mm apart on a square frame attached to a centrally-located ducted-fan wind machine. The fog was blown in the desired direction by the wind machine in the hope that any prevailing wind drift could be counteracted. Water consumption was 5m^3/h and the fan moved about 8m^3/s of air.

The fog machine was usually rotated continuously at a rate of one rotation every 3 to 4 minutes. Maximum reduction in net outwards radiation 35m from the fog machine was 80% as the plume swept over the radiometer but the fog would then clear and the sky would remain clear until the next sweep. The reduction averaged over several rotations was of the order of 15%. The very fine fog found 100m from the machine was rarely thick enough to significantly reduce outgoing radiation. A statistical analysis of data from tests made on several nights showed that average air temperature on clear frosty nights at a height of 1.5m was raised over a roughly circular area centred on the machine. Fog distribution at any instant, however, was dependent on the wind at the time; the pattern was distorted and not circular. Average air temperature 1.5m above ground was raised 1.0 to 1.9°C at 33m radius from the machine and not more than 0.6°C at 67m radius (NZAEI 1986). On occasions when ambient air temperature was above freezing, the average air temperature at grass level 35m from the fog machine rose about 2°C, at 5m elevation it was typically reduced by 0.5 to 1°C (Ireland et al 1986).

'WIND MACHINE' EFFECT

A simple calculation supports the claims that when a fog is artificially produced at a height of some 10 to 15m the tumbling of fog-laden air results in a 'wind machine' effect, raising air temperature at screen height a few degrees (Mee 1977). The experiments at Avize, Roxburgh and Hamilton suggest that this is correct. Air near the surface was warmed at least 2°C, little warming occurred near 2m, and air 5m above ground was cooled as much as 1°C when fog covered the instruments. At both Avize and Roxburgh fog was produced at a height of 6 to 8m at a rate of about 12g/m/s across-wind. When wind speed exceeded 0.6m/s the fog streamed away from the lines, in calm conditions it fell quickly towards the ground.

HEAT BALANCE

The heat balance at the ground surface when fog is used for frost control is

$$Qrn = Qc+Qe+Qg+Qfg$$

where Qfg = heat flux (sensible and latent) supplied by the fog deposited on the ground

The introduction of a thick or dense fog layer reduces the net radiation towards zero but the below-ground heat flux Qg continues to flow largely unaffected for some time. The situation is similar to that when radiation fog develops on a clear frosty night. The surface heats quickly, sensible and latent heat fluxes Qc and Qe reverse direction as heat flows from ground to air, the near-ground air temperature profile changes from inversion to lapse as the air closest to the surface warms until a new equilibrium is established.

The heat flow per unit area of the upper surface of the apple bud considered in Chapter 6 protected by an artificial fog is

$$Qr = Qc+Qe+Qfc$$

where Qfc = heat flux (sensible and latent) supplied by the fog deposited on the bud

The temperature reached by the bud depends on the fog density. Sufficient fog may strike the bud and freeze there to maintain the bud temperature near 0°C even when the surrounding air temperature is several degrees below zero. If the fog is thick enough for the net radiation from the ground to be halved and if the bud is warmed to -0.5°C by the fog as it freezes the radiant heat flux from the bud is reduced to 60W/m^2. Adding 175W/m^2 lost by evaporation the heat that has to be taken from the fog to balance the heat lost by the bud is 235W/m^2, much the same as the 261W/m^2 required for protection of the same bud by an overhead sprinkler system. When the fog is blown at 0.5m/s against one side of the bud it must have sufficient density to supply all this heat by freezing on the bud. Noting that when one gram of fog freezes on the crop in one second it will release just over 334W, the minimum required fog density is

$$235/(334*0.5) = 1.4 g/m^3$$

This is near the lower limit of density postulated by the protagonists (1 to 5g/m^3), so it appears that the freezing of fog droplets may make the major contribution to crop protection.

LATENT HEAT RELEASE

The drifting fog can release a large amount of latent heat when it freezes on a crop. Assuming half the fog is lost before reaching the crop the flux of water passing in the Avize and Roxburgh tests is 6g/m/s irrespective of wind speed. If all this water were to strike a vertical surface normal to the wind and freeze it would release 2kW/m. At Avize 90m from the line the fog layer was 1 to 3m thick close to the surface. At Roxburgh the photograph suggests the fog layer was about 5m thick 50m from the line. The maximum rate of heat release to the crop surface on the side facing the fog line would then be 2kW/m^2 for the 1m-thick layer, the minimum less than 400W/m^2 for the 5m-thick layer.

'Mee' fog lines were suspended 10m high along three sides of a one-acre square citrus orchard plot at the University of Florida, USA in 1973-74. Fog output was 30g/m/s, droplet mass median diameter was about 30um and leaf temperature was measured within 60m of the lines. Figure 12.3 (Mee & Bartholic 1979), from one night of testing, shows leaf temperature being maintained between -0.3 and +0.5°C all night, when temperature (unspecified) in a plot heated by 80 heaters was held at about -2°C, and the temperature (unspecified) in an unprotected area fell to almost -5°C, and wind speed was up to almost 1m/s. If the fog was distributed uniformly across the full 10m height between ground and fog lines the water flux passing the trees could be as high as 3g/m^2/s. Fog striking the trees would have released up to 1kW/m^2 to one side as it froze, giving the remarkable result shown in Figure 12.3.

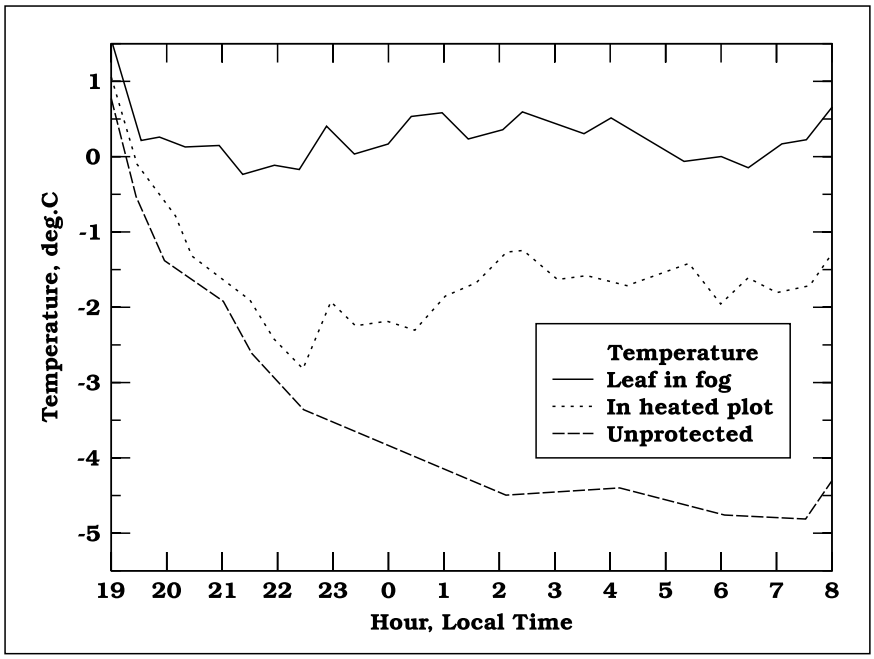

FIGURE 12.3. Leaf temperature in a Citrus orchard protected by a 'Mee' artificial fog in a radiation frost, compared with the temperature (unspecified) in a plot protected by 80 pressure-fed heaters per acre, and the temperature (unspecified) in an unprotected area, at Gainesville. (After Mee and Bartholic).

Quite apart from the inability to control wind drift, the radiation reduction achieved in practice is generally so small that latent heat of freezing must be relied on to protect crops with artificial fog. If it is assumed that artificial fog can be reliably drifted across an orchard and that radiation reduction is not significant then the water-saving advantage of a fog-producing system will be proportional to the number of trees that a parcel of fog may be expected to drift through.

Fog-wetted trees tend to stay dry on their lee sides because wetting occurs only on the sides struck by the slowly drifting, small fog droplets. Crops below overhead sprinklers tend to wet all over as the droplets are much larger and excess water runs down both sides before dripping from the underside. Fog will probably therefore protect only one side of a crop and 'patchy' protection will result.

There seems to be little indication from the reports of fogging experiments that reduction of net outwards radiation has made any significant contribution to the frost protection achieved in small areas where horizontal airflow is significant. Increased air temperature at crop height was probably due to the tumbling of fog-laden air to lower levels. It appears that the freezing of fog droplets on the surface of soil and crop maintained their temperature near 0°C. The conclusion to be drawn from the published reports is that although artificial fog is potentially valuable it has not been shown to be a practical economic method of frost protection.

CHAPTER THIRTEEN

WIND MACHINE FROST CONTROL

INTRODUCTION

Humphreys is reported as having suggested in 1914 that mixing the air close to the surface would be a good method of frost protection. By 1916 the first wind machine had appeared in California USA. A typical wind machine rating is 75kW. It brings warm air down from above to raise average air temperature at screen height by at least 2˚C over a roughly circular area of about 2ha and at least 1˚C over 4 hectares.

A hovering helicopter brings warm air down from a much greater height than a wind machine, and can be used to protect a much larger area by patrolling across the area. Redistribution of heat by wind machines and helicopters is an effective means of frost fighting when a modest amount of protection is required and wind speed is low. A 3270kg helicopter with shaft power of 435kW is able to protect about 32 hectares. The minimum power expended is similar in both cases, about $2W/m^2$, a fiftieth of the minimum used with orchard heaters.

An alternative to mixing the air near the surface is to remove the cold air closest to the surface and allow the warmer air to settle and take its place. This technique was developed in Uruguay about 1990 and followed by the first practical application and the patenting of a 'Selective Inverted Drain'.

HEAT BALANCE

The ground surface heat flux equation when a wind machine or helicopter is used for frost protection is the same as for an unprotected crop, but the conditions are different

$$Qrn = Qc+Qe+Qg$$

The wind machine mixes the air in the lowest 5 to 10m, raises the temperature near the surface a few degrees and increases the wind speed. When the apple crop considered in Chapter 6 is protected by a wind machine the net radiation loss from the slightly warmer surface may be increased by about $4W/m^2$, the sensible heat taken from the air into the surface may be increased by about $13W/m^2$, the latent heat from the frost is reduced by $1W/m^2$, and that from the soil below the surface to the surface may be reduced by about $8W/m^2$, compared with the heat flows at an unprotected surface.
The heat balance for the 10mm diameter apple bud is

$$Qr = Qc+Qe$$

This is the same as for an unprotected bud, with the exception that the air is warmed to about -2.5˚C, the bud temperature is raised above the dew point, the bud dries and latent heat falls to near zero, leaving radiant heat loss to be balanced only by air-to-crop sensible heat flow which is increased slightly by the higher wind speed created by the wind machine. When the air surrounding the bud is warmed on average 2˚C the heat loss is increased by $9.5W/m^2$ and the apple bud is warmed by 1.68˚C.

LIMITATIONS AND VARIABILITY

Frost protection with wind machines has several shortcomings. Air temperature at crop height cannot be raised more than a fraction (of the order of 50%) of the temperature inversion between screen height and 30m above ground. The crop is always raised to a lower temperature than the average air temperature produced at crop height and may not rise above the danger level.

Wind has two limiting effects. The strength of the temperature inversion decreases as wind speed increases and the warming of the air that can be achieved at crop level reduces. The protected area depends on wind speed and direction. It is displaced bodily downwind as wind speed increases, making protection less reliable as distance from the machine increases. Wind machines should not be operated in winds much exceeding 2.5m/s or when ice builds up on the propellers.

Buoyancy limits the area that can be protected by wind machines, especially in strong inversions, by forcing the warmed air to rise above the crop. To overcome this problem most wind machines are designed to thoroughly mix the air surrounding the crop. The maximum warming that can be achieved is then much less than would be the case if buoyancy was ineffective and the warmed air could be held at crop level but the protected area is maximised.

Heaters have been used in conjunction with wind machines to give better protection than wind machines or heaters alone. Under tree irrigation has also been combined with wind machines to improve protection. In some poorly designed combinations the increased buoyancy of the heated air has reduced the protected area.

Nowhere is variability more important than when wind machines are used for frost protection. The air temperature at crop level is raised a few degrees each time the jet from a wind machine or helicopter passes, then falls until the next sweep, perhaps four minutes later. The crop temperature also rises and falls in a cyclic manner, but the variation is slight. With typical crop temperature rises of only about 1 to 2˚C the day-to-day and year-to-year variations of frost temperature may easily take crop temperature below safe levels. Frost protection with wind machines is then a question of probability and risk analysis.

The frost statistics for Lincoln, New Zealand suggest that the probability of frost damage in spring would increase typically by a factor of two as the critical temperature of a crop rises by 1˚C. A wind machine that raises crop temperature by 2˚C reduces the risk of damage to about a fourth, or allows cold temperatures to occur without crop damage up to a month later than the average in spring or a month earlier in autumn.

VERTICAL-AXIS FANS

Early wind machines were sometimes made by mounting a large slow-moving propeller on a vertical axis several metres above ground. The idea was to draw the warmer air from above and allow it to spread out radially, displacing the colder air surrounding the crop. Many vertical-axis fans have been designed to do just this and have generally failed to be cost-effective. The temperature at screen height was often significantly raised close to the machine but fell rapidly over a short distance.

The reason for the poor performance of this technique was identified by an Australian study that started in winter 1948. It used three different-sized vertical-axis fans 6.1m above ground, driven by a 7kW Diesel engine (Courshee 1950). This work suggested that a large slow-speed fan could move the most heat for the least expenditure of energy. It was found,

however, that a 10.7m diameter fan rotating at 160rpm raised air temperature at least 0.56°C over only 0.4ha when there was enough heat in the air moved to warm 4 hectares. The limitation was because the buoyancy of the warmer air forced it to rise above the cooler air near the surface. It was then concluded that the greater airspeed created by a small fan produced higher momentum and allowed the warm air to carry further before buoyancy exceeded the thrust and lifted it above the crop. Calculations showed that buoyancy would limit the effect of a vertical-axis wind machine to the distance (less than 30m) at which the horizontal velocity of the warm air fell to about 0.3m/s. Here it would be moving too slowly to be useful.

The limiting effect of buoyancy is clearly shown in Figure 13.1 from an analysis of tests with a 6.4m diameter vertical-axis fan about 10m above the ground at Griffith, New South Wales, Australia from 1947 to 1949 (Frith 1950). The distance from the centre of the area of influence to the point where the temperature rise was only a quarter of that at the centre was inversely proportional to the rise at the centre (i.e. to inversion strength). The greater buoyancy of the warmer air brought down from the stronger inversion lifted it above the crop closer to the centre, protecting a smaller area. The protected area under bare almond trees was typically three times that under mature orange trees. Figure 13.2 shows that the heavily foliated Citrus trees restricted the flow of the wind machine jet at low levels, abruptly limiting the protected area at about 0.3ha (30m radius). The restriction in the almond grove was by comparison very gradual, allowing a useful amount of heat to reach a range of 60m and protect over a hectare. Air temperature increase near the surface immediately below the fan was of the order of 70% of the temperature inversion between 1 and 30 metres. (The fan was about 10m above ground so it was presumably able to draw air from at least 20m above ground.)

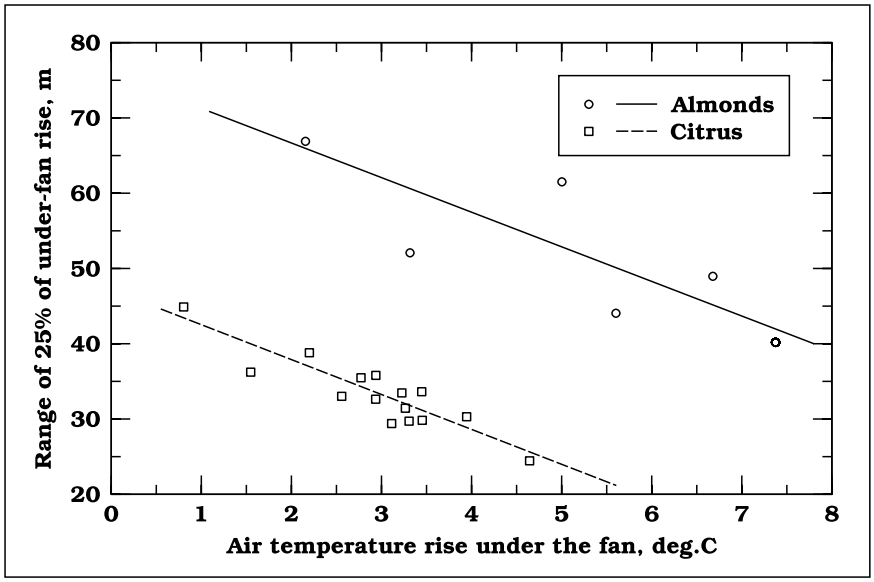

FIGURE 13.1. The distance from a vertical-axis fan at which the air temperature 0.9m above ground is increased by 25% of the increase immediately below the fan in a radiation frost at Griffith, showing the limiting effect of the greater buoyancy of the warmer air brought down from stronger temperature inversions. (After Frith).

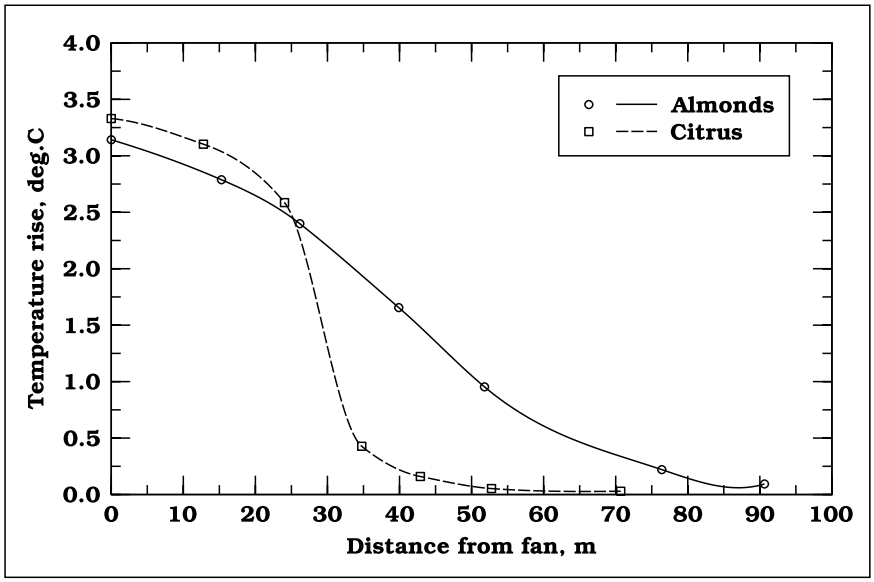

FIGURE 13.2. Air temperature increase 0.9m above ground versus distance from a vertical-axis fan in a radiation frost, in an almond grove and in an orange grove at Griffith, showing the limiting effect of the more heavily foliated citrus trees. (After Frith).

Air temperature rise more than 1˚C with vertical-axis fans with power input of the order of 10kW has generally been limited to areas less than 0.5ha (40m radius), but it can be as high as 5˚C within 10m of the machine (Angus 1962). Even smaller fans (1 to 5kW, 4.5m above ground) were tested in a vineyard at Avondale, New Zealand during winter 1948 (Palmer 1949). Air temperature 1.2m above ground was increased by 2.5˚C within about 5m of the fans and by 1˚C within a 10 to 15m radius, protecting about 0.04 to 0.07 ha. Airspeed 0.3m above ground was highest immediately below the fans, falling to 1m/s between 8 and 20m away. These results suggest that the speed of the jet from a vertical-axis fan must be at least 1m/s at the limit of the area where the air at screen height is raised on average 1˚C.

DUCTED VERTICAL-AXIS FANS

The shortcoming of the early vertical-axis fans has apparently been avoided by the simple expedient of reversing the airflow. In the ‘Selective Inverted Sump’ technique, developed in Uruguay about 1990 and patented in 1997 (Guarga Ferro 1997), ducted vertical-axis fans, such as that illustrated in Figure 13.3, draw the cooler air from near the surface, and discharge it above the warm air that settles to take its place. Whereas wind machines are designed to mix the air in order to raise the temperature near the surface, the selective inverted sump largely preserves the temperature inversion because the volume of air that has to be moved is only a small fraction of that mixed by traditional wind machines. Since only a small volume of cold air is discharged, at moderately high velocity, at least 5m above the surface, it will have little effect on the temperature of the air that settles to take its place. The power used is much less than that required by traditional wind machines.

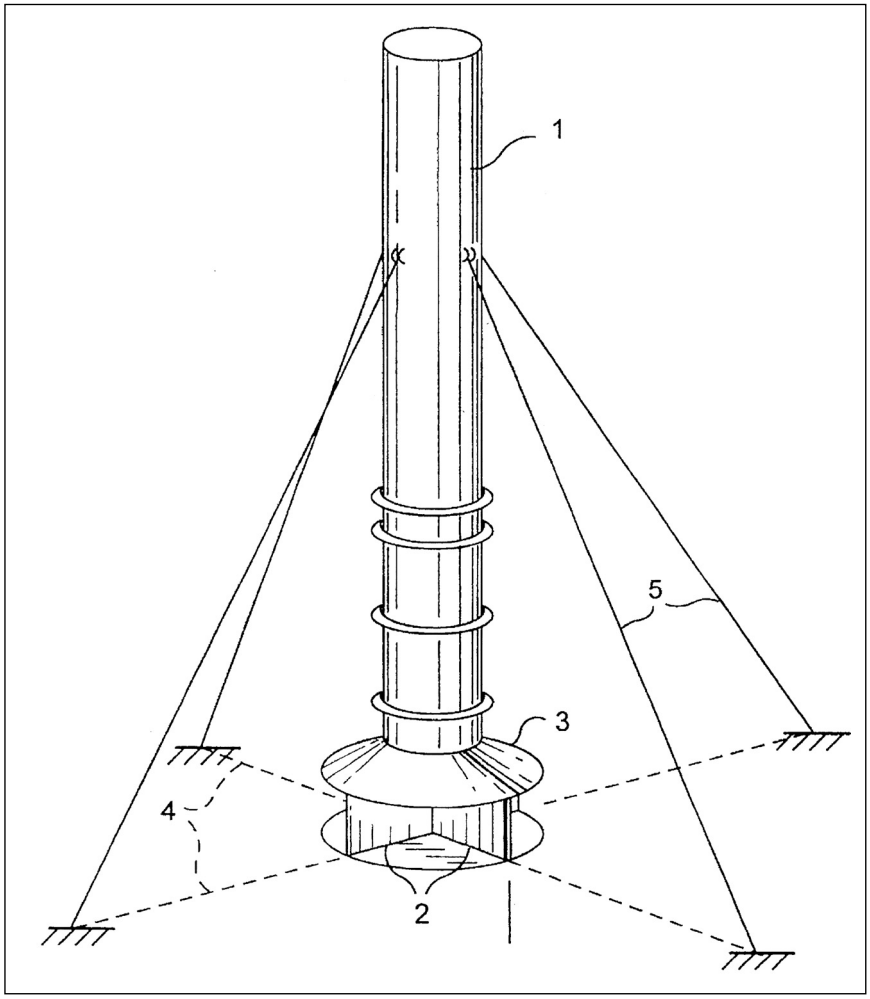

FIGURE 13.3. Schematic diagram of a 'Selective Inverted Drain' ('Selective Inverted Sump', or ducted vertical-axis fan), developed in Uruguay. (US Patent No. 5,647,165).

The report of a test using six 11kW ducted vertical-axis fans, in a Valencia orange orchard in a 54ha valley, in Young, Rio Negro, Uruguay, suggests that the air temperature in the valley, 0.5m above ground, was raised to within 0.5°C of the temperature on a ridge 12m above, on a night when it would have been expected to have been about two degrees below the ridge temperature in the absence of the system (SIS 1998).

DUCTED HORIZONTAL-AXIS FANS

A common sight in the vineyards of the Napa Valley, California USA is a ducted fan wind machine with a propeller diameter near 3m, similar to that shown in Plate 13.1. The performance of these machines does not appear to have been published in the open literature.

A technique that may be used on rare occasions in a small orchard is to tow an air blast sprayer continuously around an orchard without any spray, using the fan to mix the air near the ground. As with a wind machine, a 'return sweep' over each spot will be required every few minutes.

TILTED-AXIS FANS

Neither vertical-axis nor horizontal-axis fans are optimum. The largest protected areas are obtained by tilting the fan axis so that it blows downwards at an intermediate angle. Rotating the machine about a vertical axis so that the jet sweeps around the orchard once every few minutes further increases the protected area. A tilted-axis fan should give a confined jet with velocity sufficiently high to overcome buoyancy and induce turbulent mixing with the colder air above the crop before coming to rest. On the way down the jet will entrain a large amount of cooler air so the air reaching the crop will be cooler than that passing through the fan, even allowing for adiabatic heating (0.1°C/10m).

Australian experiments showed an optimum downwards tilt of about 20 to 25 degrees below horizontal for low-powered machines rotating up to once per minute. Figure 13.4 (Angus 1962) compares the protected areas for a 6.4m diameter fan with axis tilted 28 degrees below horizontal ("62 degrees") with the protected area of the same fan on a vertical shaft as the strength of the temperature inversion increases. The limiting effect of buoyancy is obvious for inversion between 0.9 and 9m greater than 5°C. The figure also shows that tilting the axis to near-optimum doubles, and rotating the tilted-axis fan once per minute trebles, the protected area compared with the area covered by the same fan on a vertical axis.

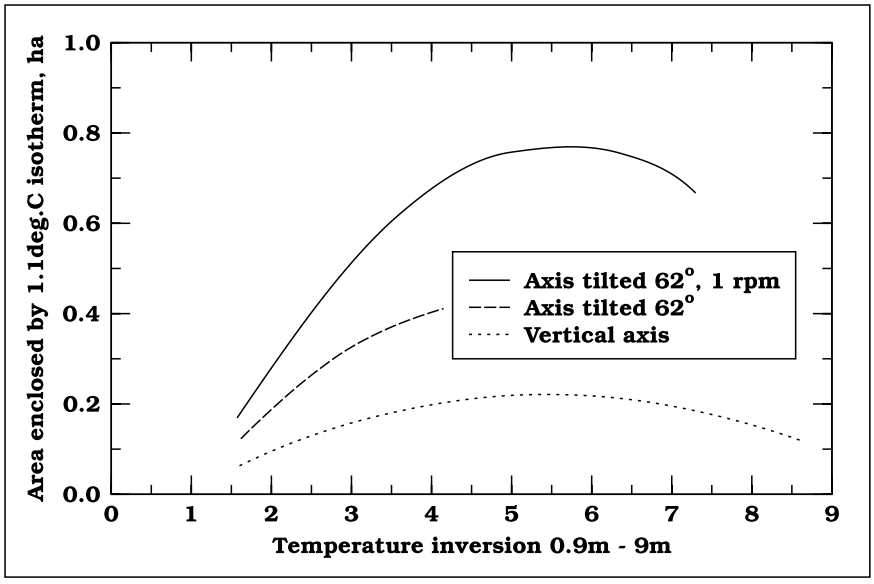

FIGURE 13.4. The area over which the air temperature 0.9m above ground, in a Citrus orchard at Griffith, is raised at least 1.1deg.C by a 6.4m diameter fan, as a function of the temperature inversion strength, the tilt of the fan axis, and the rotation of the fan axis about the vertical. (After Angus).

Air temperature at a fixed point close to a wind machine cycles up and down perhaps 2 to 4˚C as the jet sweeps around a full circle every 4 to 5 minutes. The average air temperature at crop height is then less than that of the air brought down and may be 1 to 2˚C above that of undisturbed air. A vertical-axis fan in the same situation can raise average air temperature at crop height over a small area close to the fan by at least 4˚C because the flow is continuous, not cycling.

The cycling of air temperature as the jet sweeps around is not well understood. A natural wind drift of 1m/s may move the warmed air more than 200m downwind between sweeps and replace it with cooler air. Convective heat flow to the surface will remove heat from the jet, tending to re-establish the temperature inversion. Enough heat to cool a 2m thick layer 1˚C between sweeps could be lost by convection to the surface.

NEAR-HORIZONTAL-AXIS PROPELLERS

Present-day wind machines generally follow the successful pattern reported to have been first used at San Jose Springs, California by 1928, where a horizontal-axis fan mounted on a 7.6m tower rotated about a vertical axis once every 4 minutes and protected a hectare (Gerber 1979). Buoyancy has minimal effect on the coverage of modern high-powered wind machines with near-horizontal-axis propellers about 10m above ground, such as that in Plate 13.2. The most common machine of this type manufactured in the USA is based on a design introduced in California in the early nineteen fifties. A 4.67m diameter fixed-pitch propeller, mounted on a teetering hub, tilted downwards 7 degrees below horizontal, turns at 590rpm, is driven by a 75kW engine at ground level, delivers 5kN thrust and rotates about the vertical axis once every 4 to 5 minutes.

Another wind machine design has two engines and propellers blowing in opposite directions on top of a tower. The whole assembly rotates about a vertical axis. It is reported to give about 1.6 times the temperature modification of a single-engine machine. The performance of such a machine was measured in Southern California USA in winter 1945-46 (Small 1949). The wind machine had two 90kW motors rotating once a minute on top of an 11m tower. It was located in an 8ha plot of mature navel orange trees. The effective range was 150m downwind, 61 to 91m crosswind and 46 to 61m upwind, giving an egg-shaped protected area of 1.5 to 3 hectares. The inversion strength between 1.5 and 10.7m for twelve cold nights varied from 3.9 to 10.0˚C with the average being 6.1˚C. Temperature rise when the machine started was from 1.7 to 3.3˚C near the base of the tower, decreasing with distance outwards. Temperature inversion 150m from the machine typically decreased by 2.8 to 4.4˚C within a few minutes of it being started, indicating that mixing was occurring at this distance.

The performance of a single engine 75kW machine was measured in half of an 8 hectare grove of orange trees in Florida, USA on 17 nights when temperatures approached or were below freezing over a two year period (Reese & Gerber 1969). On clear, calm nights the areas protected were inversely related to wind speed, the stronger the wind the weaker the temperature inversion and the smaller the area protected. Figure 13.5, from these tests shows the average protection available from a 75kW wind machine as a function of the strength of temperature inversion between 1.5 and 15m for both trees in leaf and bare trees. The maximum area over which air temperature rose by more than 1˚C was about 2 hectares.

Tests of a wind machine developed in New Zealand showed that the air speed produced by a four-bladed propeller on a 113kW machine, such as shown in Plate 13.3 was about 1.25 times that produced by a two-bladed propeller such as that in Plate 13.2, allowing the

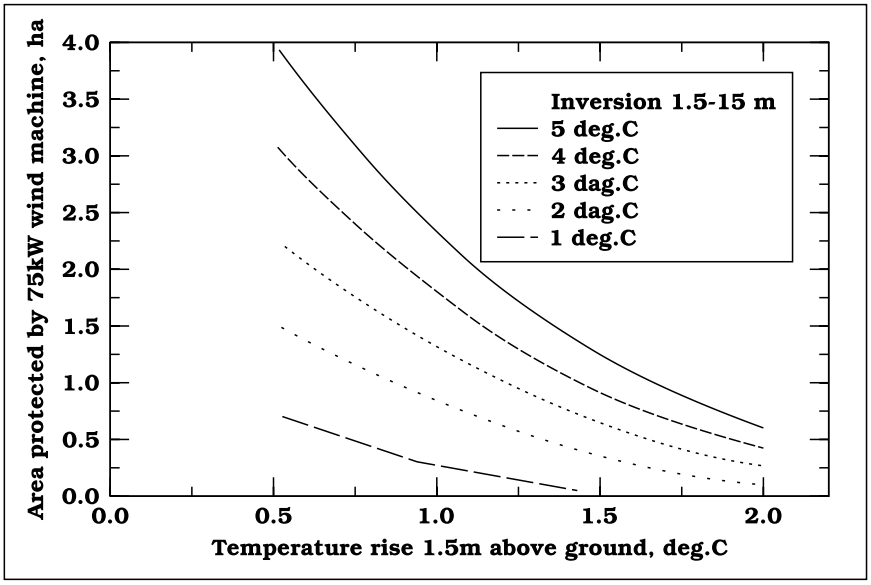

FIGURE 13.5. The area over which the air temperature 1.5m above ground, in a Citrus orchard in Florida, is raised by a 75kW wind machine as a function of the temperature inversion strength. (After Reese and Gerber).

protected area to be increased from four to six hectares. A further advantage of the four-bladed machine is that it can be run at a slower speed than the two-bladed with reduced noise, fuel consumption and general wear and tear (Frostboss 2003).

Wind usually elongates the protected area and displaces it downwind. A typical result of wind on the pattern of a 75kW machine is shown in Figure 13.6 (Bagdonas et al 1978). A wind with a speed of 1.75m/s at 2m height displaced the protected area about 60m downwind.

The rotation is not always regular, some sectors may be swept quickly, others slowly, to give appropriate protection taking account of such factors as prevailing wind, orchard shape and frost pockets. In a 1m/s wind a 65kW machine spent two thirds of the time pointing downwind and one third upwind on each revolution, and the protected area was centred about 60m downwind from the machine (Schultz 1962).

Several test reports in the literature on 68 to 186kW wind machines were compared in 1981 (Carran 1981). It was concluded that under calm conditions with typical 1.5 to 15m temperature inversions of 4.5°C the air temperature at 1.5m could be expected to rise at least 1°C over a roughly circular area of about 3.5ha centred on the wind machine.

HELICOPTERS

Hovering helicopters have much the same effect as the early vertical-axis frost fans but they have a significant advantage. A helicopter brings warmer air from a much greater height and a moving helicopter protects a very large area by patrolling back and forth across the orchard. As a result a single machine can increase the air temperature over at least 50 ha.

When a helicopter is used for frost control the flight pattern is usually designed so that the effect has disappeared before the next pass. In this way a moving 3,270kg machine with

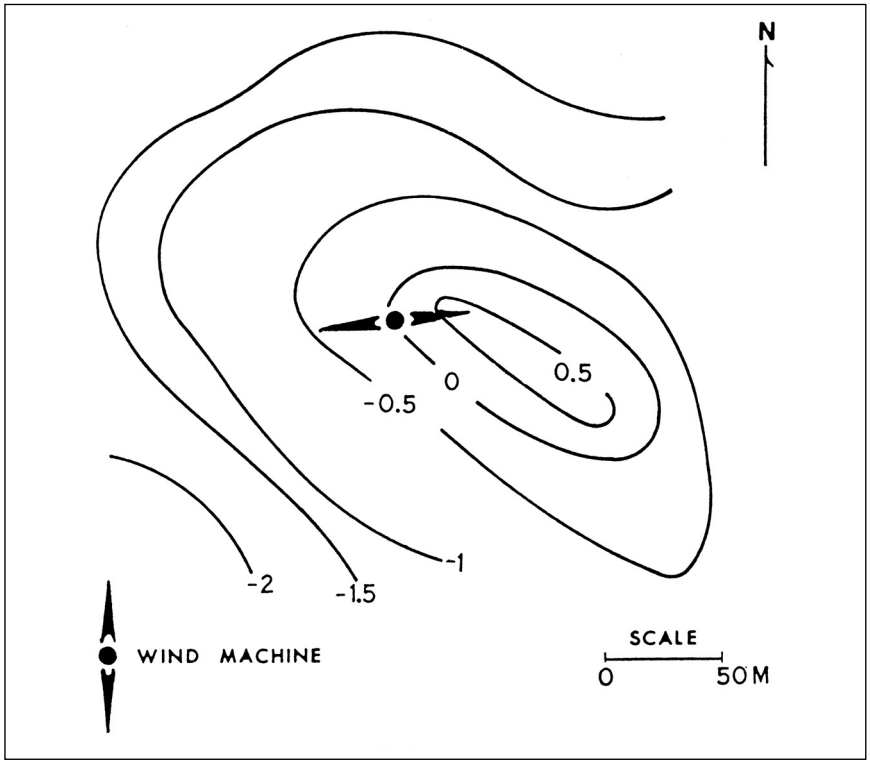

FIGURE 13.6. The displacement of the protected area around a 75kW wind machine by a 1.75m/s northwest wind. Air temperature isotherms in degrees Celsius. (Bagdonas et al).

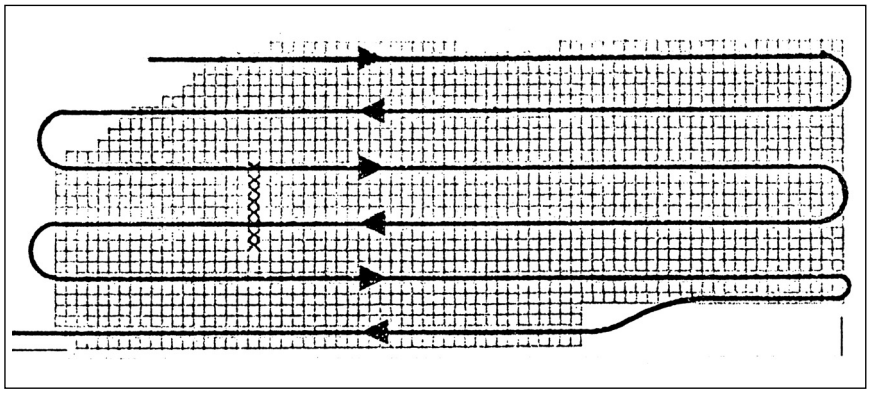

FIGURE 13.7. The typical flight pattern of a helicopter used to protect an 8-hectare lemon grove in Riverside County. The letter x marks the trees where temperatures were measured. (Miller et al).

shaft power of 435kW is able to protect about 32ha where a hovering 11,000kg helicopter may be able to maintain a continuously clear area of only 14 ha.

Helicopter performance was studied in a sheltered 40ha Valencia orange grove in the San Fernando Valley, California USA in winter 1948 (Small 1949). A machine of unspecified size was flown at various levels between 12 and 61m on a frosty night. The ground sloped gently and minimum temperatures on the higher side of the grove were 1.1 to 2.2˚C higher than on the lower level (temperatures were measured with thermographs in standard shelters). Maximum temperature rise resulted from lowest and slowest flight so most flights were made at about 12m with the landing gear clearing the trees by 1.5 to 3 metres. Flights at 4.5m/s at 12m gave temperature rises of 0.6 to 1.7˚C over a path 23m wide. Hovering for longer than 20 seconds usually raised air temperature 2.8˚C immediately below the helicopter and 1.1˚C at a radius of 23m, with no noticeable effect 30m away. The most practical flying routine was to cover the entire grove in a continuous flight taking 30 to 40 minutes and raising the air temperature about 1.1˚C. Hovering over every seventh tree for 20 seconds in the coldest areas followed this.

The effect of a 1,090kg helicopter with a 12.4m rotor was measured about sunrise in a 31ha cherry orchard at Blenheim, New Zealand on a frosty morning in spring 1979 (Heine & Wratt 1980). The wind speed and air temperature from the surface to about 90m were measured from a balloon-hoisted thermometer. Wind speed at a height of 10m was about 1.5m/s from Southwest. The temperature inversion between 1.5 and 15m was 2.2˚C and between 1.5 and 50m about 4.0˚C. Air temperature measured by a thermometer on the helicopter skid underestimated the inversion by giving high readings below 7m and low readings above. The helicopter was flown along the orchard at 8 to 10m/s at heights ranging between 23 and 61 metres. Maximum temperature measured at a height of 1.5m by an array of radiation-shielded thermistors was found 50 to 100m to the East of the North-South flight path when the helicopter flew at 46m elevation. It was 4.0˚C above the undisturbed ambient air at 1.5m. This suggests that air was brought down from at least 50m by the wake. When the helicopter flew at 61m the prevailing wind displaced the wake more than 150m to the East. The width of the wake at 1.5m when the helicopter was 23m above ground was shown by the temperature rise as it passed over the thermistor array. It had a maximum 2.3˚C above ambient and a half-width of 50m for a 1˚C temperature rise. It arrived 90sec after the helicopter passed overhead. In all single-pass flights the air cooled to one third of its maximum rise about two minutes after reaching its peak. The decay was somewhat slower when five parallel runs were made 50m apart in quick succession.

Helicopter trials on an 8ha lemon grove in Riverside County, California USA one night in winter 1970-71 increased fruit temperature from 0.3 to 1˚C. The temperature inversion between the air 1.5m above ground and the air in the helicopter 23 to 30m above ground was 5.6 to 7.8˚C. Wind speed was 0.2 to 0.7m/s at an unspecified height. Leaf, air and fruit temperatures were measured inside eight adjacent trees towards the low end of the grove. The helicopter weighed 1,337 kilograms. In the first flight, just after midnight, it flew at 9m/s about 30m above ground, covering the complete grove once according to the flight pattern shown in Figure 13.7 (Miller et al 1971). Air temperature inside the trees rose 1.9˚C ten minutes after the flight began, rising above fruit temperature by 1.7˚C. It fell below fruit temperature 15 minutes after the flight. The second flight at 2am was 15 to 23m above ground at about 2.2m/s, covering the area twice in 35 minutes. It was claimed that the air was thoroughly mixed and by the end of the flight was raised 3.3˚C. Fruit temperature rose 1˚C and remained above normal for about two hours. Air temperature fell below fruit temperature 25min after the flight. The third flight at 4.30am was 46m above ground at 9m/s,

covering the area once in 15 minutes. The maximum air response was about 0.8˚C and the air fell below fruit temperature 15min after flying ceased. The continuous air drift (0.2 to 0.7m/s) caused the helicopter down draft to be displaced in the direction of the drift so temperature rose only when the helicopter passed upwind.

A 3,270kg helicopter was flown over mature grapefruit trees in a third of a 128ha citrus grove surrounded by desert near Phoenix, Arizona USA in a series of tests in the 1973-74 and 1974-75 winters (Miles & Hinz 1976). The machine had a shaft power of 435kW and burned 160 litres of fuel per hour. Air temperature was measured at heights of 1.5 and 3.0m on a 148m-long baseline across the flight path. Temperatures at 3m were found to be the same as at 1.5m, and 1.5 to 15m inversion was typically 1 to 2˚C on the coldest winter nights. Hovering tests consistently increased the 1.5m air temperature immediately below the helicopter by more than the 1.5 to 15m temperature difference, irrespective of the height of the helicopter (5, 10, 20 and 30m). A single pass at 36m/s at a height of 9m failed to produce any measurable temperature increase at 1.5m even though the 1.5 to 15m inversion was 4.4˚C. Multiple passes North to South along the same path at 3min intervals at 11m/s in the 4.4˚C inversion and 1.4m/s crosswind produced substantial effects downwind, in addition to increasing the 1.5m temperature below the flight path. There was no effect 34m upwind but temperature 74m downwind increased one degree.

An interesting effect appeared another night when forward speed was varied. There was a 1.1m/s crosswind and 1.5m air temperature was between -1 and -4˚C. The helicopter height was unspecified. Three passes at 11m/s clearly produced up to 2˚C warming close to the flight path and a delayed warming downwind. Two passes at 4.4m/s produced a marked cooling at some sites. This was ascribed to the creation of a very turbulent wake that brought in cold air from nearby. This assumption was based on the observation, “When the helicopter passed overhead at 11m/s only a mild air disturbance was felt causing a whispering of the leaves. At 2.2m/s the helicopter produced a very turbulent downwash with leaves and twigs blowing violently beneath the aircraft.” A tentative conclusion was that a swath up to 75m wide could be protected by a 3270kg machine flying at 11m/s provided a return flight was made at least every 10min, allowing one machine to protect 40 ha.

A brief newspaper account tells of a service pioneered in Florida, USA in 1969 that was able to fly up to 25 helicopters overnight in 1988 for frost protection (AW & ST 1988). They expected to have to fly on only two nights each winter to protect Citrus crops. They typically started flying when ‘ground’ temperature was -1 to -2˚C. Warm air was brought from 12 to 18m to ground level and raised the ‘ground’ temperature as much as 3.3˚C. The helicopters flew at a height determined by measuring the atmospheric temperature inversion before operation. A 3,270kg helicopter was claimed to protect 32 ha.

It has been recommended that helicopters should work from the upwind side of the area to be protected, flying at 2 to 5m/s. The flying height for best heating effect should be based on the air temperature at the helicopter. Strategically placed, thermostatically controlled lights that come on at a preset temperature may be used to indicate areas that need attention. The pilot flies around “putting out the lights” (Evans 2001).

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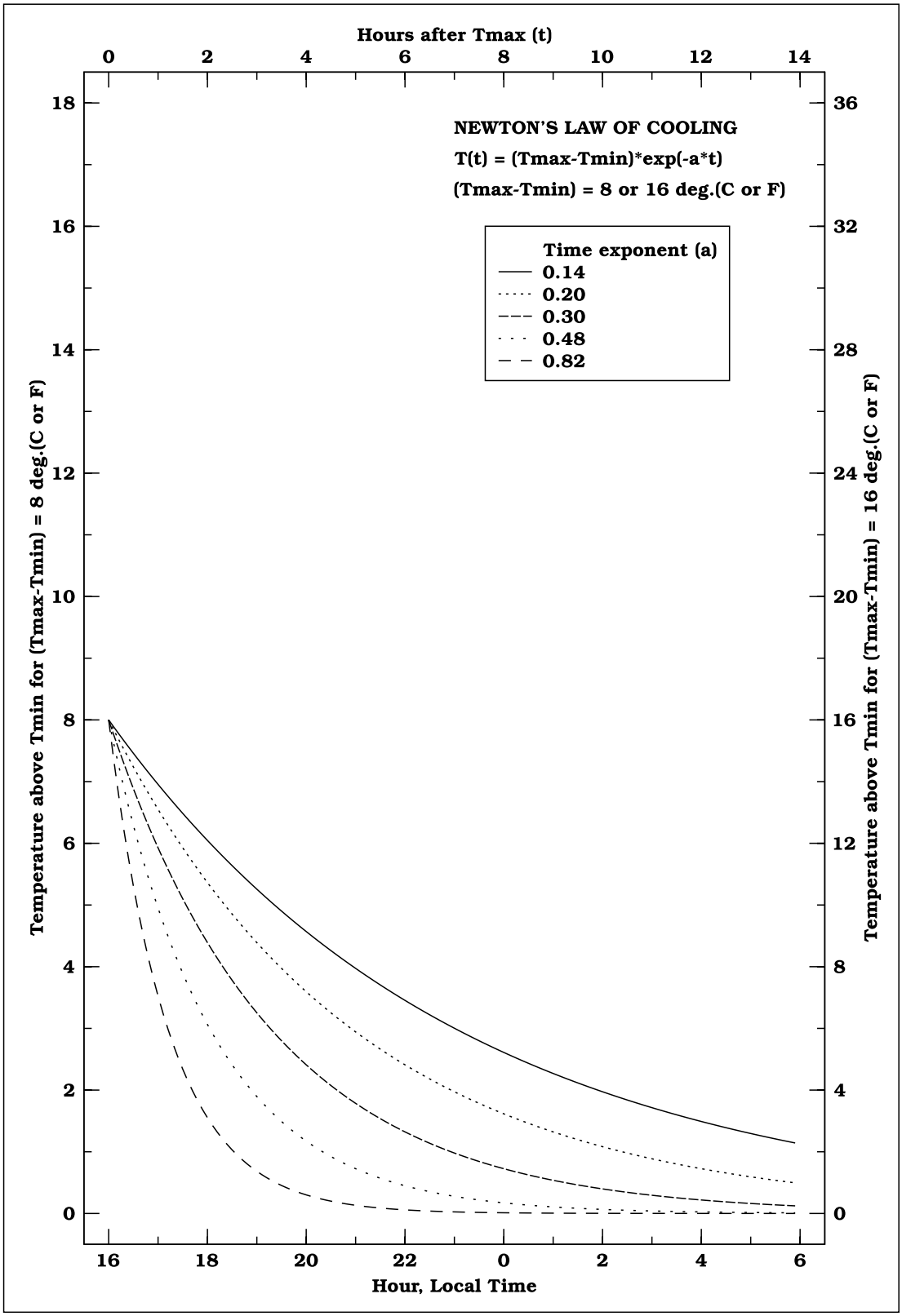
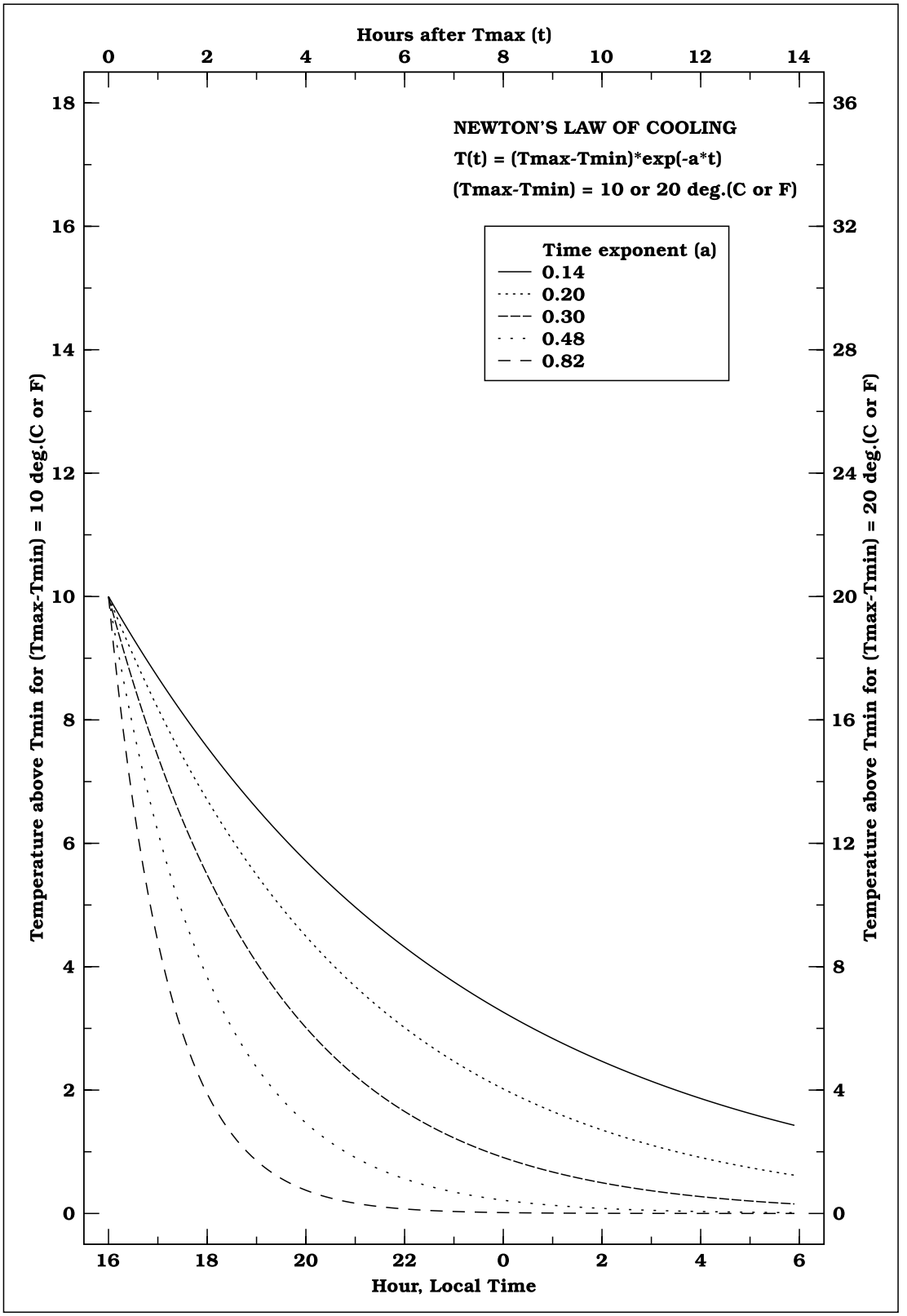
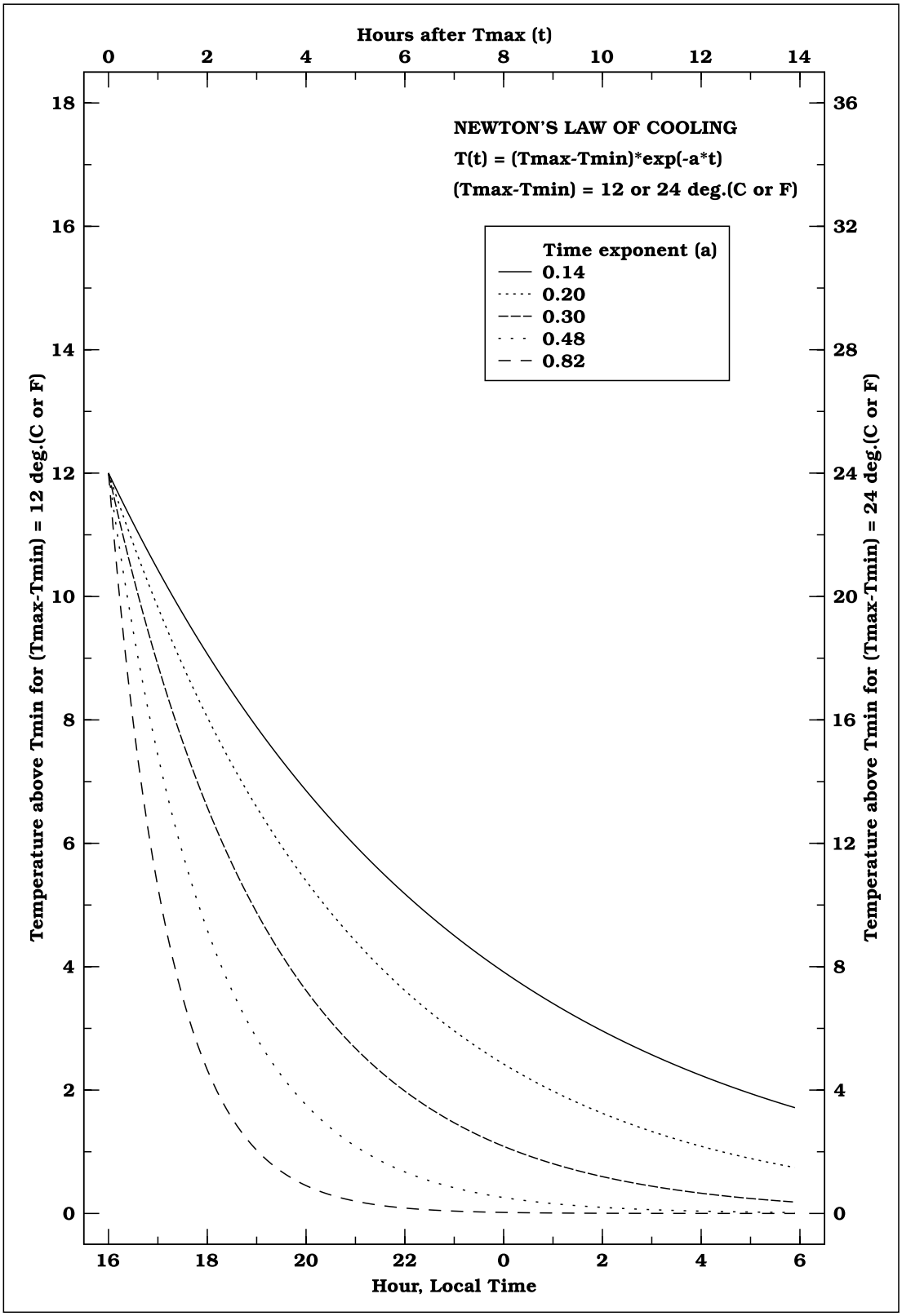
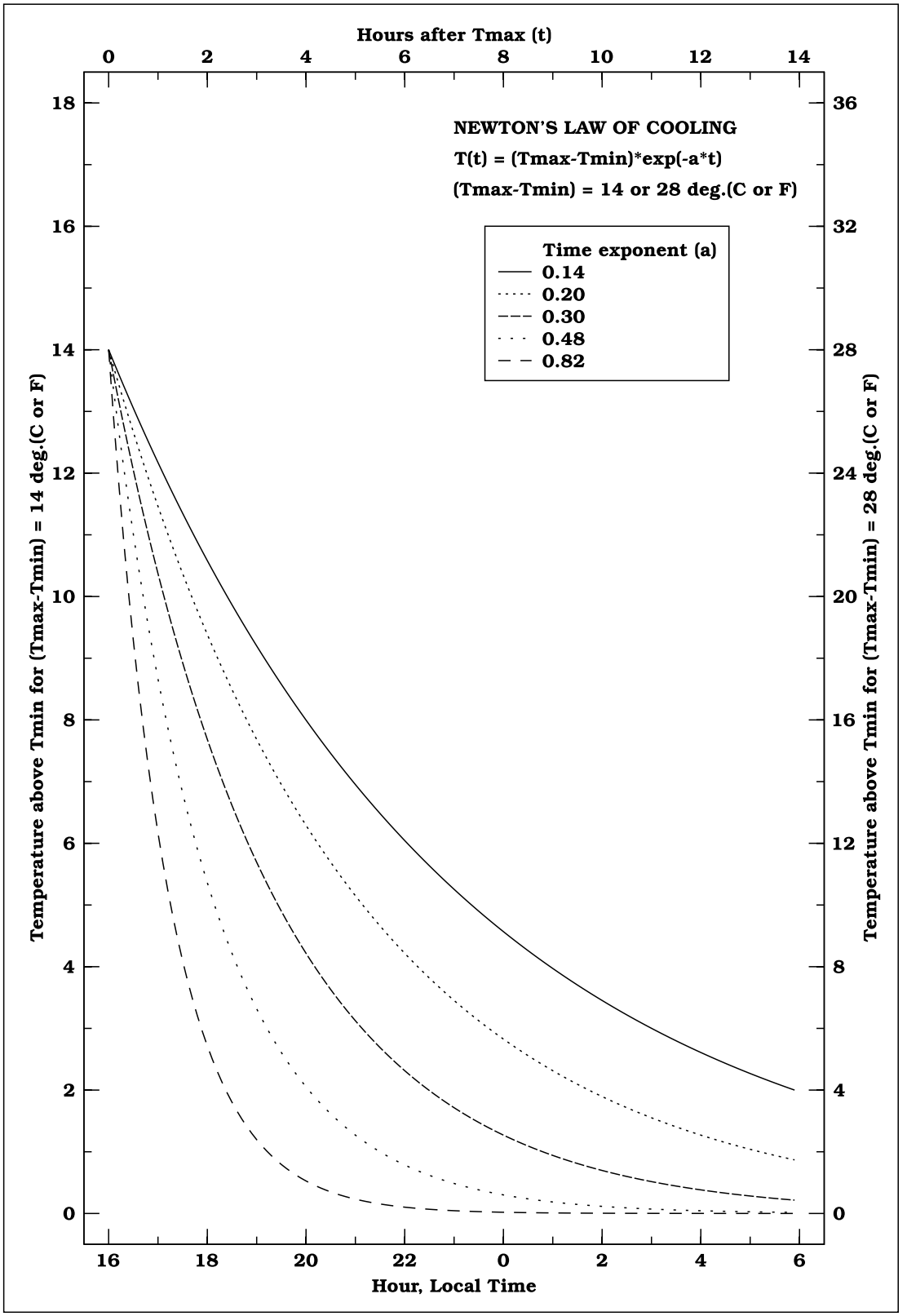
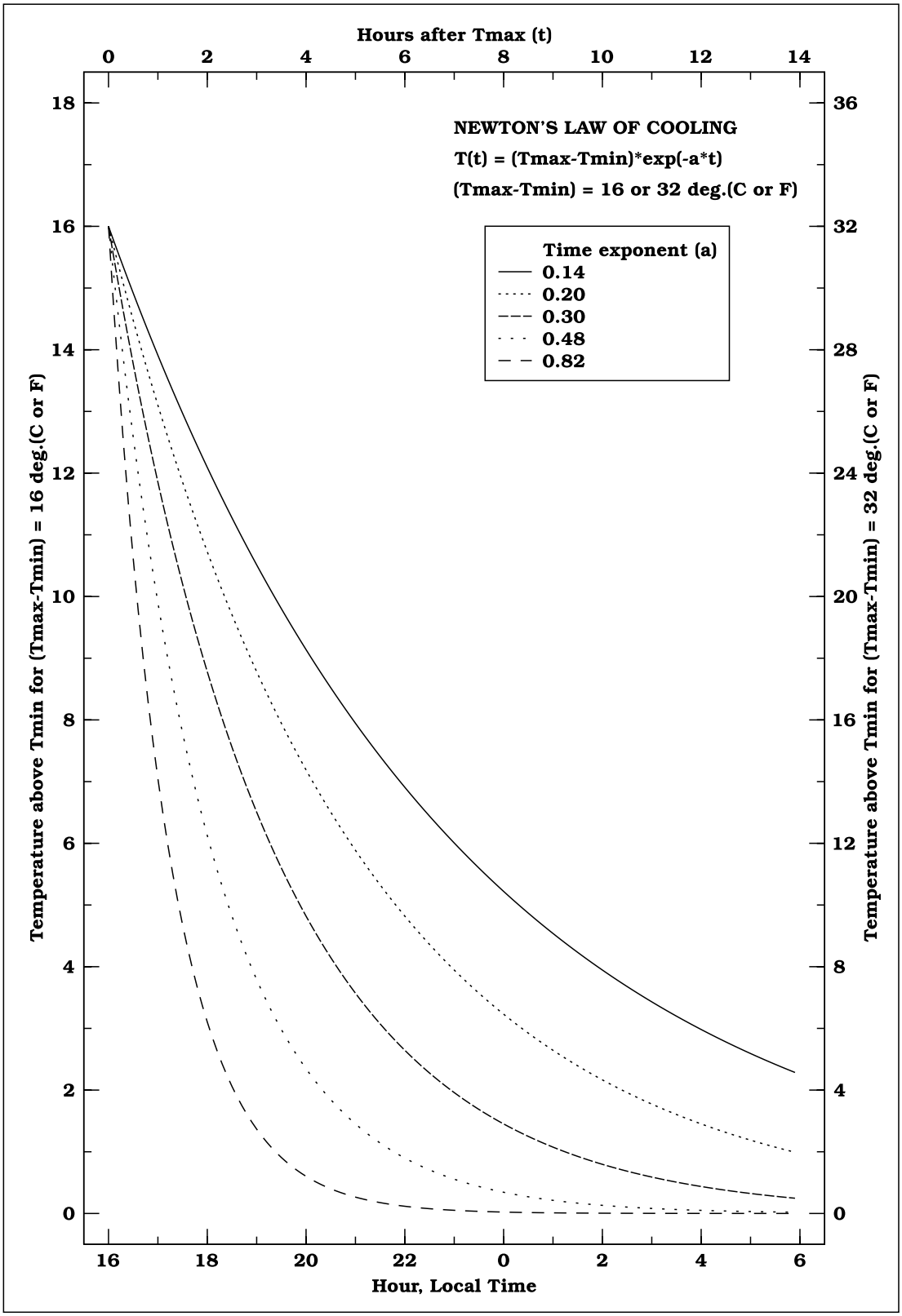
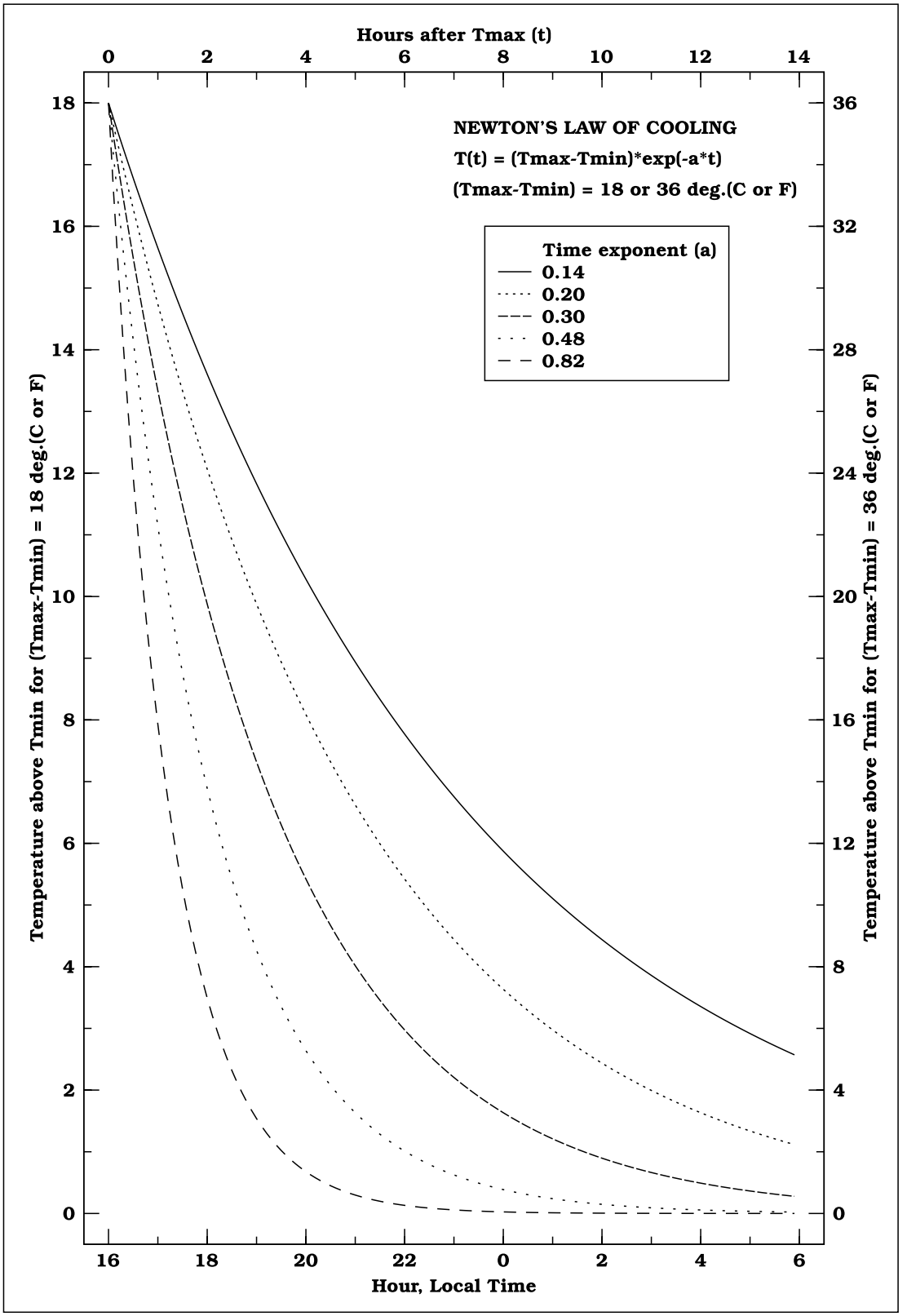

Hours after Tmax (t)
0
2
4
6
8
10
12
14
NEWTON'S LAW OF COOLING
T(t) = (Tmax-Tmin)*exp(-a*t)
(Tmax-Tmin) = 8 or 16 deg.(C or F)
Time exponent (a)
0.14
0.20
0.30
0.48
0.82
Temperature above Tmin for (Tmax-Tmin) = 8 deg.(C or F)
Temperature above Tmin for (Tmax-Tmin) = 16 deg.(C or F)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
32
36
16
18
20
22
0
2
4
6
Hour, Local Time

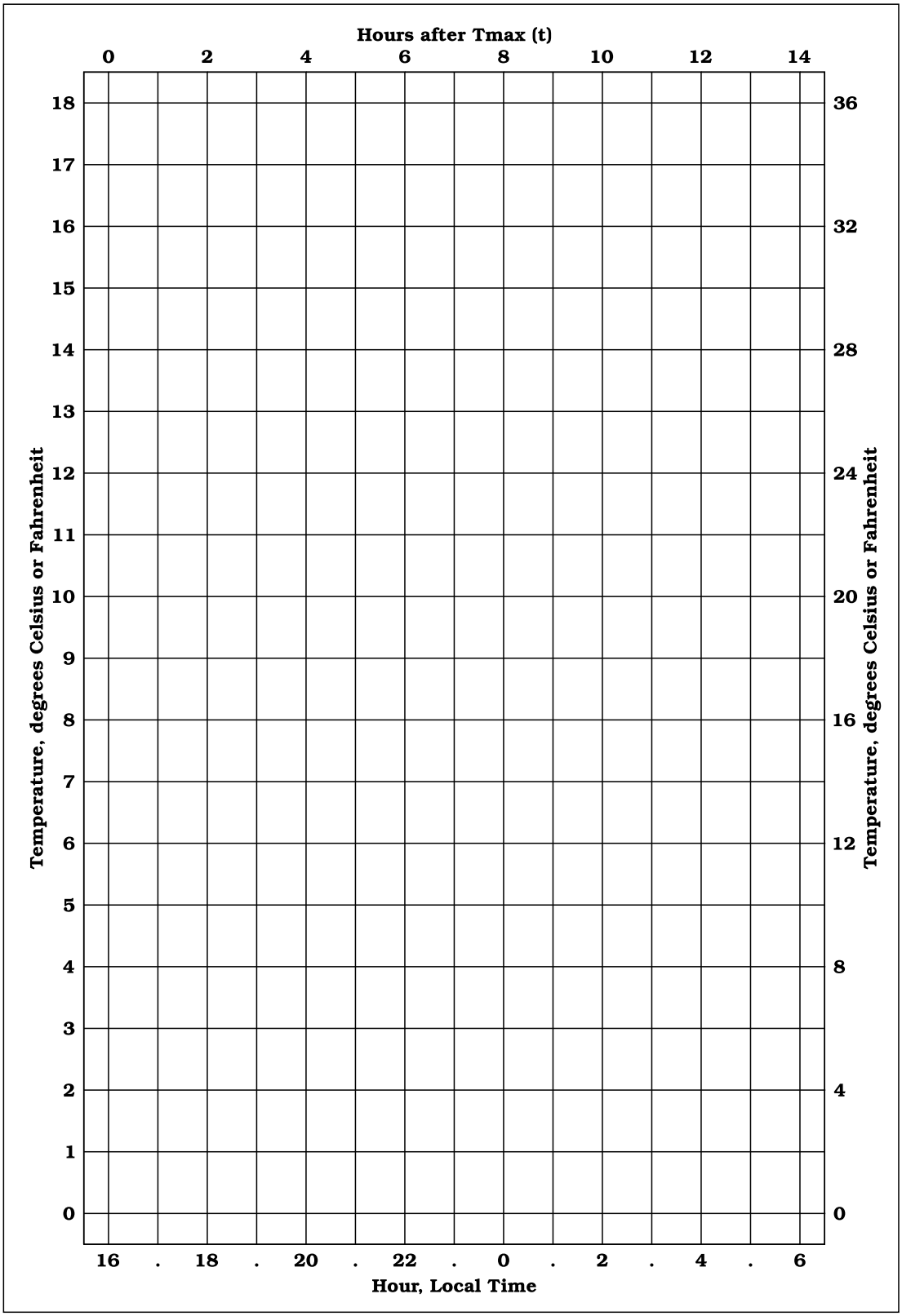

Hours after Tmax (t)
0
2
4
6
8
10
12
14
NEWTON'S LAW OF COOLING
T(t) = (Tmax-Tmin)*exp(-a*t)
(Tmax-Tmin) = 10 or 20 deg.(C or F)
Time exponent (a)
0.14
0.20
0.30
0.48
0.82
Temperature above Tmin for (Tmax-Tmin) = 10 deg.(C or F)
Temperature above Tmin for (Tmax-Tmin) = 20 deg.(C or F)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
32
36
16
18
20
22
0
2
4
6
Hour, Local Time


Hours after Tmax (t)
0
2
4
6
8
10
12
14
NEWTON'S LAW OF COOLING
T(t) = (Tmax-Tmin)*exp(-a*t)
(Tmax-Tmin) = 12 or 24 deg.(C or F)
Time exponent (a)
0.14
0.20
0.30
0.48
0.82
Temperature above Tmin for (Tmax-Tmin) = 12 deg.(C or F)
Temperature above Tmin for (Tmax-Tmin) = 24 deg.(C or F)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
32
36
16
18
20
22
0
2
4
6
Hour, Local Time


Hours after Tmax (t)
0
2
4
6
8
10
12
14
NEWTON'S LAW OF COOLING
T(t) = (Tmax-Tmin)*exp(-a*t)
(Tmax-Tmin) = 14 or 28 deg.(C or F)
Time exponent (a)
0.14
0.20
0.30
0.48
0.82
Temperature above Tmin for (Tmax-Tmin) = 14 deg.(C or F)
Temperature above Tmin for (Tmax-Tmin) = 28 deg.(C or F)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
32
36
16
18
20
22
0
2
4
6
Hour, Local Time


Hours after Tmax (t)
0
2
4
6
8
10
12
14
NEWTON'S LAW OF COOLING
T(t) = (Tmax-Tmin)*exp(-a*t)
(Tmax-Tmin) = 16 or 32 deg.(C or F)
Time exponent (a)
0.14
0.20
0.30
0.48
0.82
Temperature above Tmin for (Tmax-Tmin) = 16 deg.(C or F)
Temperature above Tmin for (Tmax-Tmin) = 32 deg.(C or F)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
32
36
16
18
20
22
0
2
4
6
Hour, Local Time


Hours after Tmax (t)
0
2
4
6
8
10
12
14
NEWTON'S LAW OF COOLING
T(t) = (Tmax-Tmin)*exp(-a*t)
(Tmax-Tmin) = 18 or 36 deg.(C or F)
Time exponent (a)
0.14
0.20
0.30
0.48
0.82
Temperature above Tmin for (Tmax-Tmin) = 18 deg.(C or F)
Temperature above Tmin for (Tmax-Tmin) = 36 deg.(C or F)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
32
36
16
18
20
22
0
2
4
6
Hour, Local Time


Hours after Tmax (t)
0
2
4
6
8
10
12
14
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
36
32
28
24
20
16
12
8
4
0
Temperature, degrees Celsius or Fahrenheit
Temperature, degrees Celsius or Fahrenheit
16 . 18 . 20 . 22 . 0 . 2 . 4 . 6
Hour, Local Time

FROST and CROPS tells for the first time how to use Isaac Newton's 'law of cooling' for on-the-spot prediction of temperature overnight in a radiation frost. Atmospheric scientist William Ireland BSc MNZIAHS brings together the practical information he considers will be of interest to those who grow plants in frost-prone areas and the methods that are used to protect valuable crops from frost damage.

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